Levitated Optomechanics

699. WE-Heraeus-Seminar

29 July – 01 August 2019
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 699. WE-Heraeus-Seminar:

This Seminar on Levitated Optomechanics brings together leading scientists and young researchers working on the control of nanoparticles suspended in vacuum by optical or electric forces. The most recent experimental and theoretical advances will be discussed of cooling untethered nano-mechanical systems into the quantum regime and of observing their rotranslational motion in the quantum-classical borderlands, as well as the perspectives of harnessing their coherent quantum dynamics for fundamental experiments and technological applications.

Levitated nanoscale particles offer a promising route towards achieving quantum control over macroscopic mechanical systems. The workshop will focus on the aspects of optomechanics that are unique to these unclamped mechanical systems. It will review cooling schemes for reaching the quantum ground state of the center-of-mass and rotational motion, and examine strategies for addressing and employing the quantized orientational degrees-of-freedom. Progress in controlling the ro-translational motion will be discussed, e.g. via conservative and non-conservative light forces, as well as the thermodynamics of these strongly isolated systems, whose interaction with ambient gaseous and radiative environments can be switched on selectively. The seminar will discuss the prospects for testing of the quantum superposition principle with levitated nanoparticles and for quantum-enhanced measurement and sensing strategies, also covering hybrid schemes where the particles are coupled to the state of individual spins or quantized circuits. The workshop will thus expose the state-of-the-art and the open problems of a promising platform for quantum technology at the interface of nanophysics and quantum optics.

Scientific Organizers:

Prof. Klaus Hornberger	Universität Duisburg-Essen, Germany E-mail: klaus.hornberger@uni-due.de
Prof. Markus Arndt	Universität Wien, Austria E-mail: markus.arndt@univie.ac.at
Dr. James Millen	King's College London, UK E-mail: james.millen@kcl.ac.uk

Program

Program

Sunday, 28 July 2019

17:00 – 21:00	Registration	
18:00	*BUFFET SUPPER and get-together*	

Monday, 29 July 2019

08:00	*BREAKFAST*	
09:00 – 09:10	Scientific organizers	**Welcome words**
09:10 – 09:55	Peter Barker	**An ultra-narrow linewidth levitated nano-oscillator for testing dissipative wavefunction collapse.**
09:55 – 10:40	Tongcang Li	**Fast rotation and nonequilibrium thermodynamics of a levitated nanoparticle**
10:40 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Martin Frimmer	**The Heisenberg limit of detection in optical levitation**
11:45 – 12:30	David Moore	**Precision searches for new physics using optically levitated sensors**
12:30 – 12:40	**Conference Photo** (in the front of the lecture hall)	
12:40	*LUNCH*	

Program

Monday, 29 July 2019

14:00 – 14:45	Benjamin Stickler	**Macroscopic quantum superposition tests with rotating nanoparticles**
14:45 – 15:30	Muddassar Rashid	**Levitated systems: Towards ultra-weak force sensing**
15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:45	Tracy E. Northup	**Towards ion-assisted levitated optomechanics: Cooling and manipulation of a nanosphere in a Paul trap**
16:45-17:15	Talitha Weiss	**Quantum motional state tomography using quartic potentials and neural networks**
17:15 – 18:00	**Poster flash presentations**	
18:15	*DINNER*	
19:30	**Poster session**	

Tuesday, 30 July 2019

08:00	*BREAKFAST*	
09:00 – 09:45	Markus Aspelmeyer	**Levitated optomechanics in the strong cooperativity regime**
09:45 – 10:30	Thomas LeBrun	**Optical microcavities for precision measurement and levitated optomechanics**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	James Millen	**New approaches to the control of levitated nanoparticles**
11:45 – 12:30	Nadine Meyer	**Resolved sideband cooling of levitated nanoparticles in a high finesse cavity**
12:30	*LUNCH*	
14:00 – 14:45	Klemens Hammerer	**Object-observer entanglement and back-action evasion in continuous positions measurements**
14:45 – 15:30	Yoshi Arita	**Rotational levitated optomechanics**

Tuesday, 30 July 2019

15:30 – 16:00	*COFFEE BREAK*	
16:00 – 16:45	Oriol Romero-Isart	**Strong quantum acousto-mechanics with a micromagnet**
16:45 – 17:15	Loïc Rondin	**Fast equilibration in the underdamped regime**
17:15 – 18:00	Mishkatul Bhattacharya	**An optical tweezer phonon laser**
18:00 – 18:15	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
18:30	*DINNER*	
19:30	**Poster session**	

Wednesday, 31 July 2019

08:00	*BREAKFAST*	
09:00 – 09:30	Rainer Kaltenbaek	**Tests of quantum physics and the case for space**
09:30 – 10:00	Dennis Rätzel	**Quantum-optomechanical systems as sensors for oscillating gravitational fields**
10:00 – 10:30	Stefan Nimmrichter	**Classical channel gravity in the Newtonian limit**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Andrew Geraci	**Gravitational-wave detection and precision sensing with optically-levitated nano-particles**
11:45 – 12:30	Gabriel Hétet	**Spin-Mechanics with particles levitating in a Paul trap**
12:30	*LUNCH*	
14:00	**Excursion**	
18:00	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	

Program

Thursday, 01 August 2019

08:00	*BREAKFAST*	
09:00 – 09:45	Nikolai Kiesel	**Thermodynamics with levitated nanoparticles**
09:45 – 10:30	Mauro Paternostro	**Entropy production in continuously measured quantum systems**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Charles Brown	**Optical, mechanical and thermal properties of superfluid Helium drops levitated in vacuum**
11:45– 12:30	Pavel Zemánek	**Nonlinear dynamics of optically levitated objects**
12:30 – 12:45	Scientific organizers	**Poster awards and closing words**
12:45	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Friday morning

Posters

Posters

Matteo Carlesso	**Testing continuous spontaneous localization with Fermi liquids**
Ondrej Cernotik	**Motional Gaussian states and gates for a levitating particle**
Timothée de Guillebon	**Nanoscale magnetic field mapping with a single spin scanning probe magnetometer at cryogenic temperature**
Maxime Debiossac	**Solving the non linear Boltzmann equation using nanoparticles inside a hollow core photonic crystal fiber**
Tom Delord	**Spin-mechanical coupling with micro-diamonds in a Paul trap**
Johannes Fiedler	**The dispersion trap**
Carlos Gonzalez-Ballestero	**Unveiling strong acoustomagnonics via force sensing**
Jonathan Gosling	**Laser refrigeration and rotation of an optically levitated Yb^{3+}:YLF nanocrystal**
Philipp Haslinger	**Attractive force on atoms due to blackbody radiation**
Yanhui Hu	**Rotational optomechanics**
Daniel Hümmer	**Quantum elastodynamical and optical properties of a rotating nanoparticle**
James March	**Towards placing a nanodiamond containing a single Nitrogen-vacancy defect in a mesoscopic superposition**
Lukas Martinetz	**Electrical cooling and control of levitated charged nanoparticles**

Posters

Darren W. Moore	**Estimation of squeezing in a nonlinear quadrature of a mechanical oscillator**
Maryam Nikkhou	**Geometric stabilisation of topological defects using optical tweezers**
Katie O'Flynn	**Levitated electromechanics**
Luca Ornigotti	**Brownian motion surviving in the unstable cubic potential**
Birthe Papendell	**Orientational quantum revivals of nanoscale particles**
Julen Simon Pedernales	**Motional dynamical decoupling for matter-wave interferometry**
Thomas William Penny	**Cooling silica nanoparticles in a Paul trap**
Markus Rademacher	**Towards laser refrigeration of NV centres on the nanoscale**
A. T. M. Anishur Rahman	**Large spatial Schrodinger cat using a levitated magnetic nanoparticle**
Andrey Rakhubovsky	**Stroboscopic higher-order nonlinearity in levitated optomechanics**
Manuel Reisenbauer	**Cavity cooling of a levitated nanosphere by coherent scattering**
François Riviere	**Thermometry of a single levitated nanodiamond**
Adrian Ezequiel Rubio López	**Radiation reaction of a jiggling dipole in a quantum electromagnetic field**

Posters

Henning Rudolph	**Entangling optically levitated nanoparticles in a single cavity**
Björn Schrinski	**Rotational friction and thermalization of quantum rigid rotors**
Troy Seberson	**Parametric feedback cooling of rigid body nanodumbbells in levitated optomechanics**
Martin Šiler	**Analysis on non-linear behavior of optically levitated particle via ensemble averaged transient dynamics**
Heming Su	**Nonlinear dynamics of optically rotated nanorods in a high Reynolds number environment**
Vojtěch Svak	**Optical binding of microparticles levitated in counter-propagating beams optical trap in vacuum**
Marko Toroš	**Detection of anisotropic particles in levitated optomechanics**
Stephan Troyer Felix Donnerbauer	**Towards microcavity cooling of nanoparticles**
Pietro Vahramian	**Rotational feedback cooling of dielectric nanorods**
Dominik Windey	**Cavity-Based 3D cooling of a levitated nanoparticle via coherent scattering**
George P. Winstone	**High frequency gravitational wave detection with levitated nano objects.**
Qi Zhu	**Dynamic simulation of optically levitated rotating particle in high vacuum**
Xunmin Zhu	**Microsphere cooling in optical tweezers in air based on FPGA controller**

Abstracts of Talks

(in alphabetical order)

Rotational levitated optomechanics

Y. Arita[1,2], E.M. Wright[3], P. Rodríguez-Sevilla[1], G.D. Bruce[1] and K. Dholakia[1]

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[2]Molecular Chirality Research Centre, Chiba University, Chiba, Japan
[3]College of Optical Sciences, University of Arizona, Tucson, USA

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This talk will describe studies that involve the interplay between matter and the angular momentum of light. This will include studies of particle dynamics in a Laguerre-Gaussian beam [1], a "perfect vortex" beam [2] and the trapping, cooling and rotation of birefringent microparticles [3,4]. Optical binding of two microparticles trapped at adjacent sites will be discussed [5,6]. New concepts for levitated optomechanics will be presented. This will include studies of rotation-translation coupling, non-trivial closed circuit dynamics and plasmonic particle trapping [7].

References

[1] M. Mazilu, Y. Arita, T. Vettenburg, J. M. Aunon, E. M. Wright, and K. Dholakia, Phys. Rev. A **94**, 053821 (2016)
[2] Y. Arita, M. Chen, E. M. Wright, and K. Dholakia, J. Opt. Soc. Am. **34**, C14 (2017)
[3] Y. Arita, A. W. McKinley, M. Mazilu, H. Rubinsztein-Dunlop, and K. Dholakia, Anal. Chem. **83**, 8855 (2011)
[4] Y. Arita, M. Mazilu, and K. Dholakia, Nat. Commun. **4**, 2374 (2013)
[5] Y. Arita, M. Mazilu, T. Vettenburg, E. M. Wright, and K. Dholakia, Opt. Lett. **40**, 4751 (2015)
[6] Y. Arita, E. M. Wright, and K. Dholakia, Optica **5**, 910 (2018)
[7] Y. Arita, G. Tkachenko, N. McReynolds, N. Marro, W. Edwards, E. R. Kay, and K. Dholakia, APL Photon. **3**, 070801 (2018)

Quantum Optical Control of Levitated Solids:
sensing, simulation and the gravity-quantum interface

M. Aspelmeyer[1,2]

[1] *Vienna Center for Quantum Science and Technology (VCQ), Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Vienna, Austria*

[2] *Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences, Boltzmanngasse 3, A-1090 Vienna, Austria*

I will report on our recent progress towards controlling the motion of levitated solids in the quantum regime [1]. I will discuss the prospects of using these systems for fundamental tests of physics, including the interface between quantum and gravitational physics [2].

References

[1] Kiesel et al., PNAS **110**, 14180 (2013); Magrini et al., Optica **5**, 1597 (2018); Delic et al., arXiv:1902.06605 (2019); Delic et al., Phys. Rev. Lett. **122**, 123602 (2019)

[2] Belenchia et al., *Phys. Rev. D* **98**, 126009 (2018)

An ultra-narrow linewidth levitated nano-oscillator for testing dissipative wavefunction collapse.

A. Pontin[1], N Bullier[1], M. Toroš[1] and P. F. Barker[1]

[1]*Dept. of Physics and Astronomy, University College London, London, UK*

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In this talk I will report on the use of a nanoparticle oscillator formed by a Paul trap to place new bounds on dissipative wavefunction collapse models. The nano-oscillator operates in high vacuum at room temperature, and we use phase sensitive detection to remove small variations in the trapping potential to measure an ultra-low linewidth of 80 μHz. We use the linewidth measurements as a function of pressure to put experimental bounds on the dissipative continuous spontaneous localisation and Diosi-Penrose models. We characterise the important noise sources for this oscillator and outline a means to achieve even lower linewidth measurements and higher Q experiments for future experiments that aim to test the macroscopic limits of quantum mechanics.

References

[1] N. P. Bullier, A. Pontin and P. F. Barker, Characterisation of a charged particle levitated nano-oscillator **arXiv:1906.09580** (2019)

[2] N. P. Bullier, A. Pontin and P. F. Barker, Super-resolution imaging of a low frequency levitated oscillator **arXiv:1905.00884** (2019)

[3] A. Pontin, N. P. Bullier, M. Toroš, P. F. Barker, An ultra-narrow line width levitated nano-oscillator for testing dissipative wavefunction collapse, **arXiv:1907.06046,** (2019)

An Optical Tweezer Phonon Laser

R. M. Pettit[1,2], W. Ge[3], P. Kumar[3], D. R. Luntz-Martin[2,4], J. T. Schultz[1,2], L. P. Neukirch[5], M. Bhattacharya[2,3] and A. N. Vamivakas[1,2,4,6]

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Phonon lasers are mechanical analogs of the ubiquitous optical laser. In this talk I will describe the theoretical proposal (from my group) and experimental realization (in the group of our collaborator A.N.Vamivakas, at the University of Rochester) of a phonon laser based on the center of mass oscillation of a nanoparticle optically trapped in vacuum. Our technique offers full control of laser gain and nonlinearity via optical feedback, and does not rely on the internal resonances of the nanoparticle. I will report on threshold behavior, coherence, subthermal number squeezing, time dynamics, phase space characterization, and the role of stimulated emission in our single mode phonon laser. Based on this discussion I will conclude that our device provides a pathway for engineering a coherent source of phonons on the mesoscale that can be applied to both fundamental problems in quantum mechanics as well as tasks of precision metrology.

References

[1] R. M. Pettit, W. Ge, P. Kumar, D. R. Luntz-Martin, J. T. Schulz, L. P. Neukirch, M. Bhattacharya and A. N. Vamivakas, Nature Photonics **13**, 1 (2019)

Optical, Mechanical and Thermal Properties of Superfluid Helium Drops Levitated in Vacuum

C. D. Brown[1], Y. Wang[1], M. Namazi[1], G. I. Harris[1], J. G. E. Harris[1]

[1]*Yale University, New Haven, CT, U.S.A.*

Optomechanical systems, in which light interacts with the motion of an object, provide an avenue to study the quantum behavior of macroscopic objects. Several goals in the field of quantum optomechanics require a combination of low temperature, low optical loss, low mechanical loss and high-precision measurement. Superfluid helium, as an optomechanical element, offers a number of advantages in these regards: extremely low optical absorption, vanishing viscosity, high thermal conductivity, and the ability to cool itself efficiently via evaporation. In recent years, superfluid optomechanical devices have made considerable advances, but their performance tends to be limited by the materials with which the superfluid is in contact. To avoid these limits and take better advantage of the superfluid's unique properties, we use magnetic levitation to suspend a drop of superfluid liquid helium in vacuum, in pursuit of using the drop's optical whispering gallery modes (WGMs) and its surface waves as an optomechanical system [1]. In this talk, we present recent measurements of mm-scale superfluid drops that are magnetically levitated in high vacuum. In particular, we will describe the formation and trapping of the drops, their evaporative cooling in the trap to ~ 330 mK, the drops' mechanical resonances, and their optical resonances.

References

[1] L. Childress, M. P. Schmidt, A. D. Kashkanova, C. D. Brown, G. I. Harris, A. Aiello, F. Marquardt, and J. G. E. Harris, Phys. Rev. A **96**, 063842 (2017)

The Heisenberg limit of detection in optical levitation

M. Frimmer, F. Tebbenjohanns, A. Militaru, F. van der Laan, D. Windey, R. Reimann, and L. Novotny

Photonics Laboratory, ETH Zürich, 8093 Zürich, Switzerland

We optically levitate a sub-wavelength sized dielectric nanoparticle in a laser trap and detect the particle's motion via the scattered light. The gained position information allows us to generate a feedback signal to cool the particle's center-of-mass motion, which equilibrates to the temperature of the thermal bath in the absence of feedback cooling. At elevated pressures, this bath is formed by the gas surrounding the particle. However, at sufficiently low pressures, it is the fluctuating forces generated by the Poissonian statistics of the trapping laser which act as the dominating thermal bath. These fluctuating forces of the light field are commonly referred to as radiation pressure short noise.

Importantly, the radiation pressure shot noise of the light field is intimately related to the imprecision of the measurement of the particle's position, which is limited by photon shot noise on the detector. It is the Heisenberg uncertainty relation which establishes the connection between measurement imprecision and measurement backaction. In this talk, we investigate the theoretical and practical limitations of detection efficiency for feedback-cooling the motion of an optically levitated nanoparticle to the ground state of motion.

Gravitational-wave detection and precision sensing with optically-levitated nano-particles

G. Winstone, N. Aggarwal, C. Montoya, W. Eom, and A. Geraci[1]

[1] *Center for Fundamental Physics, Northwestern University, Evanston, IL, USA*

In high vacuum, optically-levitated dielectric nanospheres achieve excellent decoupling from their environment, making force sensing at the zeptonewton level (10^{-21} N) achievable [1]. In this talk I will describe our progress towards using these sensors for gravitatoinal physics tests including short-distance tests of newtonian gravity and searches for gravitational waves. We will discuss our recent efforts towards detecting gravitational waves with a levitated nano-object optically suspended within a cavity [2,3]. As a complementary approach to experiments like LIGO, our experimental proposal is designed to detect gravity waves in the higher-frequency range of 10's to 100's of kilohertz, using a tabletop-scale instrument. Finally, we discuss predicted sources within such a frequency band including several Dark Matter candidates.

References

[1] Gambhir Ranjit, Mark Cunningham, Kirsten Casey, Andrew A. Geraci, *Phys. Rev. A 93, 053801 (2016).*

[2] Asimina Arvanitaki, and Andrew A. Geraci, Phys. Rev. Lett.110, 071105 (2013).

[3] A. Pontin, L.S. Mourounas, A.A. Geraci, and P.F. Barker, "Levitated optomechanics with a fiber Fabry-Perot interferometer", *New J. Phys. 20 023017 (2018).*

Object-Observer Entanglement and Back-Action Evasion in Continuous Positions Measurements

K. Hammerer[1]

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At a fundamental level Quantum mechanics dictates that a measurement correspond
s to a physical process generating entanglement among the measured object and the
measurement apparatus (and possibly the rest of the world). This entanglement inev
itably results in a disturbance of the measured system -
the famous Measurement Back Action in Quantum Mechanics. Measurement Back
Action may become the main factor limiting the sensitivity in repeated or continuous
measurements, as is the case in laser-
interferometric postion sensors such as e.g. in LIGO. I will show how Object-
Observer Entanglement and Measurement Back Action -
as well as Back Action Evasion - can be demonstrated and tested in table-
top optomechanical position sensors. Back Action Evasion can be achieved by meas
uring position with respect to an engineered reference frame corresponding to a nega
tive mass harmonic oscillator, as demonstrated by C.B. Møller, et al. [1]

References

[1] C.B. Møller, R.A. Thomas, G. Vasilakis, E. Zeuthen, Y. Tsaturyan, K. Jensen, A. Schliesser, K. Hammerer, E.S. Polzik: Quantum back-action-evading measurement of motion in a negative mass reference frame, Nature 547, 191–195 (2017)

Spin-Mechanics with particles levitating in a Paul trap

T. Delord, P. Huillery, L. Nicolas, G.Hétet[1]

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Observing and controlling macroscopic quantum systems has long been a driving force in research on quantum physics. In this endeavor, coupling individual quantum systems to mechanical oscillators is of great interest. While both read-out of mechanical motion using two-level spin systems and spin read-out using oscillators have been demonstrated by many groups, temperature control of the motion of a macroscopic object using electronic spins is still a daunting task.

We will present our observations of spin-dependent torque and dynamical back-action from a micro-diamond levitating in a Paul Trap. Using a combination of microwave and laser excitation enables the spin of nitrogen-vacancy centers to act on the diamond orientation and to observe Sisyphus cooling of the diamond libration. Further, driving the system in the non-linear regime, we demonstrate bistability and self-sustained lasing of the librational mode.

We also discuss ways to achieve spin-cooling to the ground state and present a platform that uses levitating magnets to reach the sideband resolved regime [2].

References

[1] Delord T. et al. Phys. Rev. Lett. 121 053602 (2018)
[2] Huillery P et al. ArXiv 1903.09699 (2019).

Tests of quantum physics and the case for space

R. Kaltenbaek[1,2]

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The coherent evolution of quantum states has been demonstrated for increasingly massive objects. In particular, matter-wave interferometry and corresponding techniques have been shown for test particles with masses on the range of several 10^4 atomic mass units (amu) [1,2]. While there exist proposals and interferometric techniques to perform matter-wave interferometry with dielectric particles of up to around 10^6 amu [3–5], these face limitations due to the available free-fall times and microgravity environments in ground-based experiments. Alternative approaches using magnetically [6] or electrostatically [7] levitated test particles or the observation of rotational revivals [8] may face similar limitations on ground and so far have a very low technological readiness. Here, we will discuss the concept and the progress of efforts to harness available space technology and the space environment to realize a space-based platform for future tests of the foundations of quantum physics. We will discuss the case for space as well as critical and technological challenges in the context of the MAQRO mission proposal [9,10] and the resulting QPPF study at ESA's Concurrent Design Facilty in 2018 (publication in preparation).

References

[1] S. Eibenberger, S. Gerlich, M. Arndt, M. Mayor, and J. Tüxen, Phys. Chem. Chem. Phys. **15**, 14696 (2013).
[2] J. Schätti, P. Rieser, U. Sezer, G. Richter, P. Geyer, G. G. Rondina, D. Häussinger, M. Mayor, A. Shayeghi, V. Köhler, and M. Arndt, Commun. Chem. **1**, 93 (2018).
[3] S. Nimmrichter, P. Haslinger, K. Hornberger, and M. Arndt, New J. Phys. **13**, 075002 (2011).
[4] O. Romero-Isart, A. C. Pflanzer, F. Blaser, R. Kaltenbaek, N. Kiesel, M. Aspelmeyer, and J. I. Cirac, Phys. Rev. Lett. **107**, 20405 (2011).
[5] J. Bateman, S. Nimmrichter, K. Hornberger, and H. Ulbricht, Nat. Commun. **5**, 4788 (2014).
[6] H. Pino, J. Prat-Camps, K. Sinha, B. P. Venkatesh, and O. Romero-Isart, Quantum Sci. Technol. **3**, 025001 (2018).
[7] D. Goldwater, B. Stickler, L. Martinetz, T. E. Northup, K. Hornberger, and J. Millen, Quantum Sci. Technol. (2018).
[8] B. A. Stickler, B. Papendell, S. Kuhn, B. Schrinski, J. Millen, M. Arndt, and K. Hornberger, New J. Phys. **20**, 122001 (2018).
[9] R. Kaltenbaek, G. Hechenblaikner, N. Kiesel, O. Romero-Isart, K. C. Schwab, U. Johann, and M. Aspelmeyer, Exp. Astron. **34**, 123 (2012).
[10] R. Kaltenbaek et al., EPJ Quantum Technol. **3**, 5 (2016).

Thermodynamics with levitated nanoparticles

N.Kiesel[1]

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Optical tweezers provide a powerful tool to manipulate objects at the microscale. They find applications in biophysics, material science and also provide a well-controlled experimental model system in stochastic thermodynamics, for example to investigate Brownian heat engines.

In my talk, I will present some of our recent results that use optical levitation to study phenomena in far-from-equilibrium thermodynamics. With the goal to extend the versatility of optical levitation as a platform for thermodynamics, we have started to employ holographic optical tweezer (HOT) methods to go beyond nearly harmonic potentials. In that context, I will present some of our recent results using rapidly controllable double-well potentials and their application to understand energy consumption in memories.

Optical microcavities for precision measurement and levitated optomechanics

F. Zhou, Y. Bao, D. Long, J. Gorman and T. LeBrun

Physical Measurement Laboratory,
National Institute of Standards and Technology,
Gaithersburg MD, USA

Microfabricated optical cavities offer unique advantages for optomechanical measurements. We will describe recent results using of micro Fabry-Perot cavities in silicon for precision measurement, presenting the fabrication and optical performance (spectra, transverse modes, ellipticity) of our cavities. Coupling with a mechanical resonator has enabled displacement measurement at the classical limit (less than a proton radius in a one second bandwidth) over a broad range of mechanical frequencies. We will also discuss the extension of previous work in deterministic particle launching and trapping to nanoparticle loading in microcavity-based traps.

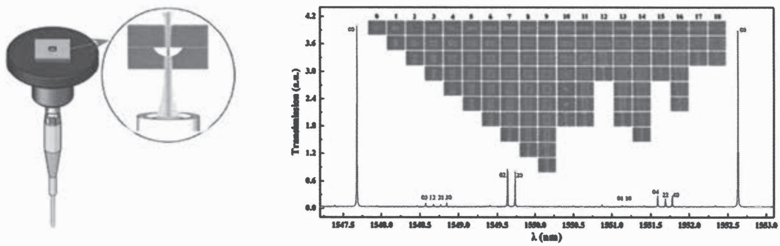

Fig. Drawing of assembled cavity, transmission spectrum and corresponding transverse modes.

Fast rotation and nonequilibrium thermodynamics of a levitated nanoparticle

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An optically levitated nanoparticle in vacuum is excellent for precision measurements. Recently, we optically levitated silica nanodumbbells in high vacuum. With a circularly polarized laser, we drove it to rotate beyond 1 GHz [1]. With a linearly-polarized laser, we observed its torsional vibration. A nanodumbbell levitated by a linearly polarized laser in high vacuum will be a novel torsion balance with a torque detection sensitivity on the order of $10^{-28} Nm/\sqrt{Hz}$. This will be sufficient to detect the Casimir torque due to the angular momentum of quantum vacuum fluctuations. This system can also be used to study the nonadiabatic dynamics and geometric phase of a fast rotating electron spin [2]. With a levitated nanoparticle under drive, we also tested the differential fluctuation theorem and a generalized Jarzynski equality that is valid for arbitrary initial states [3].

References

[1] J. Ahn, Z. Xu, J. Bang, Y.-H. Deng, T. M. Hoang, Q. Han, R.-M. Ma, T. Li. Phys. Rev. Lett., **121**, 033603 (2018).

[2] X.-Y. Chen, T. Li, Z.-q. Yin. Science Bulletin, **64**, 380 (2019).

[3] T. M. Hoang, R. Pan, J. Ahn, J. Bang, H. T. Quan, T. Li. Phys. Rev. Lett., **120**, 080602 (2018)

Resolved sideband cooling of levitated nanoparticles in a high finesse cavity

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The recent achievement of controlling a mesoscopic object down to its motional ground state [1, 2] has opened up the possibility to test the limits of quantum mechanics in our macroscopic world. However, despite growing theoretical and experimental interest in levitated systems, the ground state in Levitodynamics still remains elusive. In the context of cavity optomechanics, resolved sideband cooling of a levitated nanoparticle has recently been realised [3], with residual gas molecules and photon recoil heating being the main decoherence sources opening the way towards low phonon occupations.

Here we demonstrate the resolved sideband cooling of a levitated nanoparticle within a high finesse cavity at high vacuum. Trapping the nanoparticle in external optical tweezers allows on one hand the free positioning of the particle within the cavity field and on the other hand the additional cooling via parametric feedback cooling. The combination with well-established resolved sideband cooling techniques creates a powerful platform for controlling the centre of mass motion (COM) of a mesoscopic object. By exploiting cavity enhanced Anti-Stokes scattering we all optically cool the COM to minimum temperatures of $T \approx 10$mK for a silica particle of 235nm diameter. Power dependent laser noise heating is observed, being the main current limitation in reaching lower temperatures. In the future overcoming laser noise suppression for resolved sideband cooling will be the one of the main obstacles on the way to even lower phonon occupations in table top experiments at room temperatures.

References

[1] J. Chan, T. P. M. Alegre, A. H. Safavi-Naeini, J. T. Hill, A. Krause, S. Gröblacher, M. Aspelmeyer and O. Painter, Nature **478**, 7367 (2011)

[2] J. D. Teufel, T. Donner, D. Li, J. W. Harlow, M. S. Allman, K. Cicak, A. J. Sirois, J. D. Whittaker, K. W. Lehnert and R. W. Simmonds, Nature **475**, 7356 (2011)

[3] N.Kiesel, F. Blaser, U. Delić, D. Grass, R. Kaltenbaek, and M. Aspelmeyer, PNAS **110**, 35 (2013)

New approaches to the control of levitated nanoparticles

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As the sophistication of levitated optomechanics experiments rapidly increases, I will discuss full control over all motional and rotational degrees of freedom of levitated particles. This will enable new studies of nanothermodynamics, sensing, and the exploration of fundamental quantum physics. I will also present work on utilizing micro- optical cavities to facilitate the control of a wider mass range of nanoparticles. I will introduce an all-electrical platform for the cooling and control of nano- or micro-particles in ultra-high vacuum conditions, and discuss the technological application of this platform.

Precision searches for new physics using optically levitated sensors

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The optical trapping and manipulation of dielectric microspheres in high vacuum can enable a new class of force sensors, with sensitivity to sub-attonewton forces (i.e., nano-*g* accelerations) acting on micron-sized objects [1,2]. Such sensors are both thermally and electrically isolated from the room temperature environment, and their electric charge can be precisely controlled. Levitated microspheres in vacuum have been used to search for tiny fractionally charged dark matter particles bound in matter [3] as well as deviations from Newtonian gravity at distances below 100 μm [4]. Current results from searches for new fundamental interactions using these sensors and future applications of these techniques will be described.

References

[1] F. Monteiro, S. Ghosh, A.G. Fine, and D.C. Moore, Phys. Rev. A, 96, 063841 (2017), arXiv:1711.04675.

[2] F. Monteiro, S. Ghosh, E.C. van Assendelft, and D.C. Moore, Phys. Rev. A 97, 051802(R) (2018), arXiv:1803.04297.

[3] D.C. Moore, A.D. Rider, and G. Gratta, Phys. Rev. Lett., 113, 251801 (2014)

[4] A.D. Rider, D.C. Moore, C.P. Blakemore, M. Louis, M. Lu, G. Gratta, Phys. Rev. Lett., 117, 101101 (2016), arXiv:1604.04908.

Classical channel gravity in the Newtonian limit

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We present a minimal model for the quantum evolution of matter under the influence of classical gravity in the Newtonian limit [1]. Based on a continuous measurement-feedback channel that acts simultaneously on all constituent masses of a given quantum system, the model scales and applies consistently to arbitrary mass densities, and it recovers the classical Newton force between macroscopic masses. The concomitant loss of coherence is set by a model parameter, does not depend on mass, and can thus be confined to unobservable time scales for micro- and macroscopic systems alike. The model can be probed in high-precision matter-wave interferometry, and ultimately tested in recently proposed optomechanical quantum gravity experiments [2,3].

References

[1] K.E. Khosla, S. Nimmrichter, arxiv:**1812.03118** (2018)
[2] S. Bose et al, Phys. Rev. Lett. **119**, 240401 (2018)
[3] C. Marletto, V. Vedral, Phys. Rev. Lett. **119**, 240402 (2018)

Towards ion-assisted levitated optomechanics: Cooling and manipulation of a nanosphere in a Paul trap

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Paul traps provide an alternative to optical levitation of optomechanical systems and have recently been used to levitate graphene flakes [1], silica nanospheres [2], and defects in diamond [3,4]. We are constructing a hybrid experiment in which both the motion of a silica nanoparticle and an electric dipole transition of a single calcium ion will be coupled to an optical cavity, as a route to the preparation of quantum states of motion [5]. In this context, a Paul trap provides a means to confine both single ions and charged nanospheres.

I will discuss the experimental system under development and describe an approach we have characterized for efficient direct loading of nanoparticles into a Paul trap [6]. This approach is compatible with the ultra-high-vacuum pressures necessary for ion trapping and for future optomechanical experiments in the quantum regime. We have also developed a method to control the electric charge of the trapped particle, allowing us to tune the particle's oscillation frequency as well as to measure its mass precisely. Finally, I will report on recent measurements of both electrical and optical feedback cooling of the particle's secular motion.

References

[1] B. E. Kane, *Phys. Rev. B* **82**, 115441 (2010)
[2] J. Millen, P. Z. G. Fonseca, T. Mavrogordatos, T. S. Monteiro, and P. F. Barker, *Phys. Rev. Lett.* **114**, 123602 (2015)
[3] T. Delord, L. Nicolas, L. Schwab, and G. Hétet, *New J. Phys.* **19**, 033031 (2017)
[4] G. P. Conangla, A. W. Schell, R. A. Rica, and R. Quidant, *Nano Lett.* **18**, 3956 (2018)
[5] A. C. Pflanzer, O. Romero-Isart, and J. I. Cirac, *Phys. Rev. A* **88**, 033804 (2013)
[6] D. S. Bykov, P. Mestres, L. Dania, L. Schmöger, T. E. Northup, arXiv:1905.04204 (2019)

Entropy production in continuously measured quantum systems

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The entropy production rate is a central object in non-equilibrium thermodynamics. It characterises thermodynamic irreversibility and sets important quantitative bounds to the efficiency of thermodynamic cycles.

Yet, we lack definitions of this quantity that are easily manageable and general enough to encompass various experimentally interesting set-ups. In this work, we characterise the excess entropy produced by a continuously monitored Gaussian system – a.k.a., the situation often encountered in actual laboratories – due to the observation process.

We isolate the entropy production rate using the dynamics of the system in phase space. The key result that we achieve is a generalised second-law which account for the information acquired by measuring the system [2].

We then apply such novel formalism to the dynamics of a levitated optomechanical system, showing the observability of the framework and its relevance for the energetics of the system [1,3].

References

[1] M. Brunelli *et al.*, Phys. Rev. Lett. **121**, 160604 (2018)

[2] A. Belenchia, L. Mancino, G. Landi, and M. Paternostro, to appear (2019)

[3] L. Mancino, A. Belenchia, et al. to appear (2009)

Quantum-optomechanical systems as sensors for oscillating gravitational fields

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Metrology with quantum sensors promises unprecedented precision. Applied to gravitational fields, this may lead to experiments beyond Newtonian gravity like searches for fifth forces (modified gravity) or experiments on the interface of gravity and quantum mechanics. It may be possible to detect the gravitational field of light or gravitational waves from presistent sources. In this presentation, I will introduce the description of opto-mechanical systems driven by oscillating gravitational fields that we developed in the last year. This includes an analysis of their full time evolution. Furthermore, I will report on the subsequent investigation of the performance of such systems as gravity sensors.

Levitated Systems: Towards ultra-weak force sensing

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Levitated systems have invited growing interest partly due to their capabilities to reach high mechanical quality factors, $Q_m > 10^9$, and for studies in force sensing, fluctuation theorems, nanothermodynamics and macroscopic quantum systems, to name a few. A levitated anisotropic particle, untethered from its environment can exhibit a rich spectrum of rotation and translational motion. Rotational motion is acutely dependent upon the size and shape of an object and the properties of the light that imparts angular momentum to the particle. It is also highly susceptible to changes to its environment, i.e. gas pressure or external non-conservative forces.

In this talk, I will present work on translational and rotational optomechanics, specifically looking at how rotation, libration, nutation and precession motion can arise in levitated systems. I will present a proof-of-principle experimental work on precession motion, which we use for detecting optical torques as small as, 10^{-23} Nm, with the potential to reach torque sensitivities of 10^{-31} $\mathrm{Nm}/\sqrt{\mathrm{Hz}}$ [1].

REFERENCES

[1] Rashid *et al.*, Phys. Rev. Lett. 121, 253601

Strong Quantum Acousto-Mechanics with a Micromagnet

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We theoretically show how to strongly couple the center-of-mass motion of a micromagnet in a harmonic potential to one of its acoustic phononic modes. The coupling is induced by an oscillating magnetic field gradient, which couples the center-of-mass motion with a magnonic mode, and a homogeneous magnetic field that tunes in resonance the intrinsic magneto-elastic coupling of the magnonic mode with a given acoustic phononic mode. We show how, within experimentally feasible parameters, the magnetic fields can be tuned to either cool the center-of-mass motion to the effective temperature of the acoustic low entropy mode, leading to ground state cooling in a cryogenic environment, or enter in the strong coupling regime, which can be used to probe and manipulate an acoustic mode via the center-of-mass degree of freedom. Our results apply to levitated micromagnets as well as micromagnets deposited on a nanomechanical clamped oscillator.

Fast equilibration in the underdamped regime

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Numerous conventional thermodynamics cycles use quasi-static transformations that allow staying near equilibrium at any time. However, such transformations require virtually an infinite time. Speeding up the process leads to the generation of out of equilibrium states. Similarly, under a sudden change of state, the system will require a relaxation time before reaching equilibrium. Recently, engineering of swift equilibration protocols has been proposed to tackle this issue. Such protocols have been demonstrated in the overdamped regime [1], but a more general demonstration is still to be done [2,3]. We present here our recent progress on the observation of shortcut to equilibration with a levitated particle where environmental parameters are easily controllable.

References

[1] Martínez et al. Nat Phys **12**, 843–846 (2016).
[2] Chupeau et al. New J. Phys. **20**, 075003 (2018).
[3] Li et al Phys. Rev. E **96,** 012144 (2017).

Macroscopic quantum superposition tests with rotating nanoparticles

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Observing quantum features in the rotation dynamics of a levitated nanoparticle offers a viable route to test the quantum superposition principle and to realize ultra-precise torque sensors [1]. In this talk I will present the quantum and classical theory of how dielectric nanorotors interact with laser fields [2] and ambient environments [3]. I will argue that optically or electrically cooling the rotation into the quantum regime opens the door for the observation of macroscopic orientational quantum revivals [1], a complete recurrence of the initial orientation of a nanorotor after integer multiples of the revival time.

References

[1] Stickler, Papendell, Kuhn, Millen, Arndt, and Hornberger, New J. Phys. **20**, 122001 (2018)

[2] Stickler, Nimmrichter, Martinetz, Kuhn, Arndt and Hornberger, Phys. Rev. A **94** 033818 (2016)

[3] Stickler, Schrinski, and Hornberger, Phys. Rev. Lett. **121**, 040401 (2018)

Quantum Motional State Tomography using Quartic Potentials and Neural Networks

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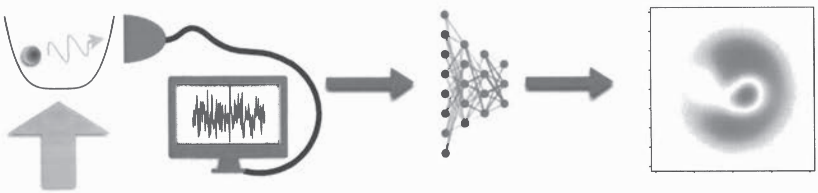
Cooling levitated nanoparticles into their motional ground state and then preparing a non-classical state is a central goal of the field of levitated optomechanics. The exceptionally high isolation of levitated systems is a key advantage for this purpose but turns into a challenge when trying to measure and verify the prepared state. We investigate the motion of a particle in a quartic potential, where the non-linearity allows to gather information about higher order moments of the quantum state, even if only the position-trajectory is measured. Thus, a quantum state tomography protocol could consist of the state preparation within a usual harmonic potential, followed by an evolution in a quartic potential. We successfully train neural networks to deduce the initially prepared quantum state from simulated trajectories of position and position variance and return the associated density matrix. In particular, we show and investigate this neural-network based quantum state reconstruction for states of different dimensionality. We discuss how the achieved fidelity depends on the provided trajectory length and study the impact of decoherence. Moreover, we discuss the feasibility of our approach ranging from a trapped ion to a levitated nanoparticle and find that it depends on the interplay of decoherence and non-linearity strength. Notably, the proposed scheme for quantum state tomography does not explicitly depend on the quarticity of the potential: Any other non-linearity could in principle be used as well to reconstruct a quantum state in the described way.



Nonlinear dynamics of optically levitated objects

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Recent progress in optical control of mechanical systems opens new ways to investigate a wide variety of mechanical effects in thermodynamics and statistical physics, stochastic dynamics and quantum mechanics. In near future, the most interesting in these fields are nonlinear stochastic effects which autonomously transform environmental noise to useful mechanical effects. A nonlinearity of potential allows mechanical systems to sustain limit cycle oscillations characterized by statistics different from a thermal equilibrium one. Such mechanical processes can be therefore principally used as a primary source of coherent mechanical displacement and mechanical oscillations. They might allow to do autonomously mechanical work at micrometer and nanometer distances. In a long term vision, such nonlinear processes might be extremely interesting in the underdamped regime that has been already reached for some cases.

We provide experimental demonstrations of underdamped and overdamped dynamics of optically levitated objects in nonlinear potentials, analyze their motion and system parameters. Working in vacuum with a circularly polarized Gaussian optical trap, transverse spin momentum drives the underdamped motion of a probe particle far beyond thermodynamic equilibrium. Constrained by optical gradient forces, we first observe spin-driven Brownian motion and, subsequently, the formation of thermally excited orbits. Our work shows how observations of the underdamped motion of probe particles can illuminate our understanding of the nature and morphology of momentum flows in arbitrarily structured light fields as well as providing a test bed for elementary non-equilibrium statistical mechanics. We also provide a proof-of-principle analysis of particles dynamics in nonlinear potential, both in underdamped and overdamped regime, that is applicable also in quantum mechanics.

References

[1] V. Svak, O. Brzobohatý, M. Šiler, P. Jákl, J. Kaňka, P. Zemánek, S. Simpson, Nature Communications **9**, 5453 (2018)

[2] M. Šiler, L. Ornigotti, O. Brzobohatý, P. Jákl, A. Ryabov, V. Holubec, P. Zemánek, R. Filip, Physical Review Letters **121**, 230601 (2018)

[3] M. Šiler, P. Jákl, O. Brzobohatý, A. Ryabov, R. Filip, P. Zemánek, Scientific Reports **7**, 1697 (2017)

Abstracts of Posters

(in alphabetical order)

Testing continuous spontaneous localization with Fermi liquids

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Collapse models describe phenomenologically the quantum-to-classical transition by adding suitable nonlinear and stochastic terms to the Schrödinger equation, thus (slightly) modifying the dynamics of quantum systems. Experimental bounds on the collapse parameters have been derived from various experiments involving a plethora of different systems, from single atoms [1] to gravitational wave detectors [2]. Here, we give a comprehensive treatment of the continuous spontaneous localization (CSL) model, the most studied among collapse models, for Fermi liquids. We consider both the white and non-white noise case. Application to various astrophysical sources is presented.

References

[1] M. Bilardello, S. Donadi, A. Vinante, and A. Bassi, Physica (Amsterdam) **462A**, 764 (2016).
[2] M. Carlesso, A. Bassi, P. Falferi, and A. Vinante, Phys. Rev. D **94**, 124036 (2016).

Motional Gaussian states and gates for a levitating particle

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Coherent scattering has recently attracted attention as a means of controlling the motion of levitated particles in three dimensions using a single optical cavity. In these systems, scattering of photons from the trapping field to a cavity mode has been used to cool all three modes of the centre-of-mass motion of levitated particles [1,2]. The possibility of employing coherent scattering for more general quantum control has, however, not yet been discussed in the literature. Here, we present strategies for generating nonclassical correlations and for engineering interactions between motional modes of levitated particles using coherent scattering. We expand the theory developed by Gonzalez-Ballestero *et al*. [3] to realize more general bilinear interactions in levitated optomechanics with coherent scattering. Going beyond the simple stationary picture, we introduce amplitude modulation as an important tool to modify the optomechanical interaction and discuss how it can be used to resonantly enhanced certain parts of the interaction, allowing, for example, strong one- and two-mode squeezing of motion. Our results thus show the potential of using coherent scattering for full quantum control of the motion of levitated particles.

References

[1] U. Delic *et al*., Phys. Rev. Lett. **122**, 123602 (2019)
[2] D. Windey *et al*., Phys. Rev. Lett. **122**, 123601 (2019)
[3] C. Gonzalez-Ballestero *et al*., arXiv:1902.01282 (2019)

Nanoscale magnetic field mapping with a single spin scanning probe magnetometer at cryogenic temperature

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The development of magnetic imaging systems at the nanoscale has been of central importance for many scientific advances, in particular in nanomagnetism. Part of actual challenges are displaced towards materials displaying magnetic properties only at low temperatures. Imaging in these conditions creates new constraints on pre-existing techniques, which increases experimental challenges. These last years have seen the development of scanning magnetic field microscope based on the electron spin resonance of the NV center, a colored center in diamond [1]. These devices, combining great sensitivity and excellent spatial resolution, have brought great results in nanomagnetism at room temperature [2-4]. This technique relies on the measure of the Zeeman displacement between two sublevels of the electronic spin of a unique NV center, and it can be adapted at cryogenic temperatures, bringing thereby great hopes in sensitive and resolved magnetic imaging.

This work describes the implementation of such a microscope, at cryogenic temperatures, in parallel with the results obtained with this experimental apparatus, in particular concerning the study of (Ga,Mn)(As,P), a ferromagnetic semiconductor displaying very interesting properties towards high-performance memory architectures. A part of this work has also been dedicated to study the processes at stake in the relaxation of NV centers in nanodiamonds in the prospect of using it as a fluctuating magnetic fields sensor.

References

[1] Rondin, L. et al., Magnetometry with nitrogen-vacancy defects in diamond, *Rep. Prog. Phys.* **77**, 056503 (2014).

[2] Rondin, L. et al., Stray-field imaging of magnetic vortices with a single diamond spin, *Nat. Commun.* **4**, 2279 (2013).

[3] Tetienne, J.-P. et al., Nanoscale imaging and control of domain-wall hopping with a nitrogen-vacancy center microscope, *Science* **344**, 1366-1369 (2014).

[4] Tetienne,J.-P. et al., The nature of domain walls in ultra thin ferromagnets revealed by scanning nanomagnetometry., *Nat. Commun.* **6**, (2015).

Solving the non linear Boltzmann equation using nanoparticles inside a hollow core photonic crystal fiber

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We report on the application of levitated nanoparticles for pressure and flow sensors inside a hollow core photonic crystal fiber. When a pressure gradient is applied between the two ends of the fiber, the resulting pressure and flow distributions are described by the Boltzmann equation. So far, experiments have been limited to small pressure gradients and ex situ detection techniques. Here we show that the pressure and flow profiles can be measured locally using levitated nanoparticles inside a hollow core fiber, even for large pressure gradients. Comparing our measurements with predictions from a direct simulating Monte Carlo method of the nonlinear Boltzmann equation, we extract an accommodation factor of 0.9 for air molecules on silica surface. Our result provides an experimental test of the non linear Boltzmann equation and offers new applications in the field of microfluidics.

Spin-mechanical coupling with micro-diamonds in a Paul trap

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Inspired by experiments on cold atoms and ions, optomechanics has made major steps toward realizing quantum mechanics experiments with macroscopic mechanichal oscillator [1,2]. Hybrid system such as an NV spin coupled to a mechanical oscillator offer an other promising approach [3] which can be combined with a levitated oscillator to profit from its isolation once under high vacuum [4].

Here, an ion trap is used to levitate a micro-diamond under atmospheric pressure and low vacuum. NV spins ensembles within it can be coherently manipulated and exhibit similar properties with and without levitation.
Interestingly we show the Paul trap confine not only the center of mass but also the rotation of the diamond, yielding an angularly stable diamond and, under low vacuum, harmonic motion for its librational modes (angular oscillation) at kHz frequencies.

Using highly NV-doped micro-diamond and a uniform magnetic field we show actuation of the diamond angular position via magnetic spin-dependent torque and perform mechanically detected electron spin resonance [5]. Further, the NV spin long lifetime allows using back-action on the librational modes to cool down or amplify the librational modes [5]. This effect bears a strong analogy with Sisyphus cooling and cavity optomechanics, indeed we similarly also observe a spin-spring effect on the libration confinement resulting from the conservative part of the back-action.

Finally we propose and show first steps using levitating ferromagnets in order to enter the coherent spin-mechanical coupling : we use magnetic confinement of ferromagnets to attain librations higher than bulk NV spin decoherence rate and propose sensing the magnetic field it generates with bulk NV spins microns away [6].

References

[1] M. Aspelmeyer, et al. Reviews of Modern Physics, 86(4), 1391 (2014) .
[2] I. Marinković, et al. Physical review letters, 121(22), 220404 (2018).
[3] P. Rabl, et al. Physical Review B, 79(4), 041302 (2009).
[4] J. Gieseler, et al. , Physical review letters, 109(10), 103603 (2012).
[5] T. Delord, et al. , arXiv preprint :1905.11509 (2019).
[6] P. Huillery, et al, arXiv preprint :1903.09699 (2019).

The dispersion trap

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Dispersion interactions are forces caused by the ground-state fluctuations of the electromagnetic fields, typically resulting in attractive forces between the constituents. However, recent investigations have shown a change to repulsive forces by adding an environmental medium to the particles [1]. Such repulsive force can be combined with attractive forces to create a trap for the particle.

We will present two ways for such balancing with attractive forces: (i) for nanoparticles in balance with buoyancy, which we apply to ice nanoparticles that stabilise at a certain position below the water surface [2], and (ii) with the dispersion force itself. The latter effect is caused by the crossings of the different dielectric functions involved in the system. Due to these crossings situations can be created with a repulsive short range (non-retarded) force and an attractive long range (retarded or thermal) force [3]. We will introduce the concepts of medium-assisted dispersion forces [4] and illustrate the application of a particle trap induced by these.

References

[1] J. Fiedler *et al.*, J. Phys. Chem. A **121**, 9742 (2017)
[2] P. Thiyam *et al.*, J. Phys. Chem. C **122**, 15311 (2018)
[3] J. Fiedler *et al.*, submitted (2019)
[4] F.A. Burger *et al.*, EPL **121**, 24004 (2018)

Unveiling strong acoustomagnonics via force sensing

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One of the main research focuses in levitated optomechanics has been the control of the external degrees of freedom, e.g. the center of mass (COM) motion. Recently, however, part of the focus has shifted to their internal degrees of freedom (phonons, magnons, excitons, etc), which, due to the extreme confinement and isolation provided by nanoparticle levitation, have been predicted to behave in different fashion than both bulk matter and less isolated nanoparticles (e.g. in solution) [1]. Despite these predictions, experimentally probing the internal excitations of a levitated nanoparticle is a challenging task, due to their highly isolated character. This difficulty is especially acute for excitations which interact very weakly with the electromagnetic field such as acoustic phonons.

In this work, we propose a way to experimentally probe the acoustic phonon modes of a levitated nanomagnet (NM) by measuring its COM position. We first develop a quantum theory of both the acoustic phonons and the magnons supported by a NM, and analytically compute their interaction Hamiltonian. Such interaction is shown to be both qualitatively and quantitatively different than for larger, less isolated spheres [2], with coupling rates about 11 orders of magnitude larger. This strong coupling allows for a probing of the acoustic modes by measuring the state of the magnons, namely the magnetization of the NM. In the second part of our work, we show how we can transduce the magnetization into COM motion by applying a weak inhomogeneous magnetic driving, that couples the magnons to the COM motion. We continue by demonstrating how the presence of acoustic modes close to resonance with a given magnon has a sharp impact in the position power spectral density. Such effect is found to be well within experimentally measurable signals, thus allowing to probe the internal phonons using the well refined tools for force sensing in levitated nanoparticles [3]. Our work could pave the way toward studying new regimes of condensed matter and light-matter interaction in levitated nanoparticles.

References

[1] A. E. Rubio López, C. Gonzalez-Ballestero, O. Romero-Isart, PRB **98**, 155405 (2018)

[2] X. Zhang, C.-L. Zou, L. Jiang, H. X. Tang, Sci. Adv. **2**, e1501286 (2016)

[3] C. Gonzalez-Ballestero, J. Gieseler, O. Romero-Isart (In preparation)

Laser refrigeration and rotation of an optically levitated Yb^{3+}:YLF nanocrystal

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An obstacle for many levitated optomechanical systems is the heating of a trapped nanoparticle due to the absorption of the laser light[1]. This increase in the internal temperature of the nanoparticle leads to instabilities in the optical trap and eventually decoherence in the system. This heating becomes even more significant issue as lower pressures are reached. Laser refrigeration[2] by utilising anti-Stokes fluorescence is a promising solution to combat this heating. This type of internal cooling has been demonstrated on a levitated nanocrystal of Yb^{3+}:YLF with temperatures as low as 130K realised[3]. To potentially reach lower temperatures and to also improve trapping, bipyramidal nanocrystals of Yb^{3+}:YLF have been colloidally grown and trapped. In this poster, we present the characterisation of crystal temperature and their orientation and rotation in an optical trap.

References

[1] J. Millen, T. Deesuwan, P.F. Barker and J. Anders, "Nanoscale temperature measurements using non-equilibrium Brownian dynamics of a levitated nanosphere", *Nature Nanotechnology*, vol. 9, no. 6, pp. 425-429, 2014.

[2] P. Pringsheim. Zwei bemerkungen über den unterschied von lumineszenz- und temperaturstrahlung. *Zeitschrift für Physik* , 57(11-12):739–746, 1929.

[3] A T M Anishur Rahman and P.F. Barker, "Laser refrigeration, alignment and rotation of levitated Yb^{3+}:YLF nanocrystals", *Nature Photonics*, vol. 11, no. 10, pp. 634-638, 2017.

Attractive force on atoms due to blackbody radiation

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Blackbody (thermal) radiation is emitted by objects at finite temperature with an outward energy-momentum flow, which exerts an outward radiation pressure. At room temperature e. g. a cesium atom scatters on average less than one of these blackbody radiation photons every 10^8 years. Thus, it is generally assumed that any scattering force exerted on atoms by such radiation is negligible. However, particles also interact coherently with the thermal electromagnetic field[2] and this leads to a surprisingly strong force acting in the opposite direction of the radiation pressure. Using atom interferometry, we find that this force scales with the temperature of the heated source object (293 – 450 K) to fourth power[1]. The force is in good agreement with that predicted from an ac Stark shift gradient of the atomic ground state in the thermal radiation field[2].

References

[1] P. Haslinger, M. Jaffe, V. Xu, O. Schwartz, M. Sonnleitner, M. Ritsch-Marte, H. Ritsch, H. Müller, Attractive force on atoms due to blackbody radiation, *Nat. Phys.* 14 257–260 (2018)

[2] M. Sonnleitner, M. Ritsch-Marte, H. Ritsch, Attractive Optical Forces from Blackbody Radiation, *Phys. Rev. Lett.* 111 23601 (2013)

Rotational Optomechanics

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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 [1-3], yielding great potential for detecting a wide range of forces [4-6].

In this project, full control and cooling of all degrees of freedom (center-of-mass and rotational degrees of freedom) will be researched and demonstrated [7]. 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 testing macroscopic quantum superposition experiment by probing the orientational quantum revivals of a nanorotor will be studied [8]. In addition, Real-time force sensing based on phase sensitive measurements of a rotating nanorod will be investigated [9].

References

[1] F. Tebbenjohanns, M. Frimmer, A. Militaru, V. Jain and L. Novotny, Phys. Rev. Lett. 122, 223601 (2019).

[2] D. Windey, C. Gonzalez-Ballestero, P. Maurer, L. Novotny, O. Romero-Isart and R. Reimann, Phys. Rev. Lett. **122**, 123601 (2019).

[3] U. Delic, M. Reisenbauer, D. Grass, N. Kiesel, V. Vuletic and M. Aspelmeyer, Phys. Rev. Lett. **122**, 123602 (2019).

[4] T. Hoang, Y. Ma, J. Ahn, J. Bang, F. Robicheaux, Z. Yin and T. Li, Phys. Rev. Lett. **117**, 123604 (2016).

[5] G. Ranjit, M. Cunningham, K. Casey and A. A. Geraci, Phys. Rev. A **93**, 053801 (2016).

[6] M. Rashid, M. Toros, A. Setter and H. Ulbricht, Phys. Rev. Lett. 121, 253601 (2018).

[7] S. Kuhn, A. Kosloff, B. A. Stickler, F. Patolsky, K. Hornberger, M. Arndt and J. Millen, Optica **4**, 356 (2017).

[8] B. Stickler, B. Papendell, S. Kuhn, B. Schrinski, J. Millen, M. Arndt and K. Hornberger, New J. Phys. **20**, 122001 (2018).

[9] S. Kuhn, B. Stickler, A. Kosloff, F. Patolsky, K. Hornberger, M. Arndt and J. Millen, Nature Commun. **8**, 1670 (2017).

Quantum Elastodynamical and Optical Properties of a Rotating Nanoparticle

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An optically trapped nanoparticle in vacuum can rotate with frequencies up to GHz, as recently reported in [1]. The resulting inertial forces alter its elastic and optical properties. This change in turn affects the optical forces experienced by the nanoparticle, and more generally the elastic and inelastic scattering of light. We derive, from first principles, a parametric quadratic Hamiltonian describing the dynamics of acoustic phonons as a function of the rotational frequency within the framework of linear elastodynamics [2]. For spherical particles in particular, a largely analytical description is feasible. The Hamiltonian is then used to study, in dependence of the rotational frequency of the particle, (i) the linear stability [3], (ii) the Brillouin spectrum, and (iii) the shape and electric polarizability of the nanosphere.

References

[1] R. Reimann, M. Dodorer, E. Hebestreit, R. Diehl, M. Frimmer, D. Windey, F. Tebbenjohanns, and L. Novotny, Phys. Rev. Lett. 121, 033602 (2018).

[2] D. Hümmer, et al. In preparation.

[3] K. Kustura, C. C. Rusconi, and O. Romero-Isart, Phys. Rev. A 99, 22130 (2019).

Towards Placing a Nanodiamond Containing a Single Nitrogen-Vacancy Defect in a Mesoscopic Superposition

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Nanodiamonds containing a single negatively charged nitrogen-vacancy defect (NV^-) have been proposed as a vehicle for attempts to place a mesoscopic object in a quantum superposition [1, 2, 3, 4]. In order to minimize coupling to the environment, the nanodiamond is levitated. Although levitation of nanodiamonds has been demonstrated with optical tweezers, it was found that the diamonds are prone to graphitisation at pressures lower than 10 mbar due to their absorbing laser light [5]. This problem can be partially solved with purer nanodiamonds [6]. A more complete solution to this is to use a magneto-gravitational trap [7] which we are now setting up. Once successfully levitated, the spin of the NV^- defect would be initialised into a superposition state of the form $1/\sqrt{2}\left(|1\rangle + |-1\rangle\right)$. A magnetic field gradient would then spatially separate the $|\pm1\rangle$ components of the spin state, resulting in a mesoscopic superposition. "Motional dynamic decoupling" would help to both reduce decoherence and increase the superposition distance [8]. The components should then be brought back together to interfere. Finally, tilting the superposition with respect to gravity would impart a gravitational phase that could be detected through the matter wave interferometer providing evidence of the mesoscopic superposition.

References

[1] M. Scala, M. S. Kim, G. W. Morley, P. F. Barker & S. Bose, Physical Review Letters **111,** 180403 (2013)
[2] C. Wan *et al.*, Physical Review Letters **117**, 143003 (2016)
[3] Z.-Q. Yin, T. Li, X. Zhang and L. M. Duan, Physical Review A **88**, 033614 (2013)
[4] S. Bose & G. W. Morley, arXiv:1810.07045 (2018)
[5] A. T. M. A Rahman *et al.*, Scientific Reports **6**, 21633 (2016)
[6] A. C. Frangeskou *et al.*, New Journal of Physics **20**, 043016 (2018)
[7] J.-F. Hsu, P. Ji, C. W. Lewandowski & B. D'Urso, Scientific Reports **6**, 30125 (2016)
[8] J. S. Pedernales, G. W. Morley & M. B. Plenio, arXiv:1906.00835 (2019)

Electrical cooling and control of levitated charged nanorotors

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Levitating a charged nanoscale particle between two capacitor plates and integrating the latter into an electric circuit provides a promising route to supplement techniques from levitated optomechanics. The electrical current induced by the ro-translational motion of the charged particle can be used to detect, manipulate, and cool the particle motion [1-2]. A combination of electric feedback and resistive cooling in a parallel RLC circuit enables to reach the quantum regime, even in the presence of circuit-induced heating due to Johnson-Nyquist noise. We discuss, how the cooled particle quantum state can be manipulated with scalable electric circuitry, opening the door for levitated quantum electromechanics.

References

[1] D. Goldwater et al., Quantum Sci. Technol. **4**, 024003 (2019)
[2] L. S. Brown et al., Rev. Mod. Phys. **58**, 233 (1986)

Estimation of squeezing in a nonlinear quadrature of a mechanical oscillator

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Abstract

Processing quantum information on continuous variables requires a highly nonlinear element in order to attain universality. A measurement-induced method for applying an element of this type, the cubic phase gate, for quantum circuits involves the use of a non-Gaussian ancilla known as the cubic phase state. A necessary condition for the cubic phase state is that noise in a selected nonlinear quadrature should decrease below the level of classical states in order to to obtain the cubic phase gate with less noise than classical cubic nonlinearities [1]. A reduction of the variance in this nonlinear quadrature below the ground state of the ancilla, a type of nonlinear squeezing, is the resource embedded in these non-Gaussian states and a figure of merit for nonlinear quantum processes. Quantum optomechanics with levitating nanoparticles trapped in nonlinear optical potentials is a promising candidate to achieve such resources in a flexible way. We provide a scheme for reconstructing this figure of merit in quantum optomechanics, analysing the effects of mechanical decoherence processes on the reconstruction and show that all mechanical states which exhibit reduced noise in this nonlinear quadrature are nonclassical.

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[1] K. Miyata, H. Ogawa, P. Marek, R. Filip, H. Yonezawa, J. Yoshikawa, and A. Furusawa, Phys. Rev. A **90**, 060302(R) (2014).

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Geometric stabilisation of topological defects using optical tweezers

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The creation and manipulation of topological defects has attracted widespread attention as they have been shown to play an important role in physical and biological systems. The softness, geometric order, and optical response of liquid crystals (LCs) position them as fertile ground for investigating topological defects.

Here we study the creation and stabilization of an odd number of topological defects on small colloidal particles immersed in a LC device. These particles are topologically equivalent to a sphere of genus g=0. Oppositely charged pairs of topological monopoles are created by applying a laser-induced local temperature quench. Individually, these monopoles are inherently stable, but since they are paired and oppositely charged, they tend to attract each other and annihilate when their separation becomes less than $< 40\ \mu m$. To stabilize the defect monopoles, a gigantic particle is needed [1,2]. Micro-helices and micro-grooved-rods are suitable colloidal particles for the stabilization of topological monopoles with micro-meter separation. The features on the particles stabilize the defects and prevent them from moving toward each other. Further, by controlling the number of and space between grooves on the grooved-rods, any odd number of topological defects with precise spatial positions can be created and stabilized. Such a rod could therefore carry a huge number of oppositely charged defects, which could have interesting consequences for colloidal interactions. From the fundamental aspect, this work fully supports the Gauss–Bonnet theorem, stating that the total topological charge of all hedgehog defects on an object should be equal to g-1.

References

[1] M. Nikkhou, M. Škarabot, S. Čopar, M. Ravnik, S. Žumer, and I. Muševič, Nature Physics **11**, 183 (2015).

[2] M. Nikkhou, M. Škarabot, and I. Muševič, Phys. Rev. E, **93**, 062703 (2016)

Levitated Electromechanics

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Following advances in levitated optomechanics, we explore levitated electromechanics (LE) as a novel alternative method for trapping and controlling micro- and nanoparticles. LE provides an opportunity to circumvent the limitations of traditional optical tweezers, allowing robust trapping of particles with a wide range of sizes and compositions, from metals to biological material. This platform also offers a clear route to miniaturization, force sensing and signal processing. We present the theory of LE, and the latest experimental efforts in realising a levitated electromechanical system with all-electrical detection and state control.

Brownian motion surviving in the unstable cubic potential

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Trajectories of an over-damped particle in a highly unstable potential diverge so rapidly, that the variance of position grows much faster than its mean. Description of the dynamics by moments is therefore not informative [1]. This makes experiments challenging and breaks down a standard statistical analysis of unstable mechanical processes and their applications.
Instead, we propose and analyse local directly measurable characteristics, which overcome this limitation. We discuss the most probable particle position (position of the maximum of the probability density) and the local uncertainty in an unstable cubic potential, both in the transient regime and in the long-time limit.
The maximum shifts against the acting force as a function of time and temperature. Simultaneously, the local uncertainty does not increase faster than the observable shift. In the long-time limit, the probability density naturally attains a quasi-stationary form. An experimental verification of the latter has been pursued [2], where even the long-time limit phenomena has been observed. We moreover explain this quasi-stationary process as a stabilisation via the measurement-feedback mechanism, the Maxwell demon, which works as an entropy pump. Rules for measurement and feedback naturally arise from basic properties of the unstable dynamics. Observed thermally induced effects are inherent in unstable systems. Their detailed understanding will stimulate the development of stochastic engines and amplifiers and later, their quantum counterparts.

References

1. R. Filip and P. Zemánek, Journal of Optics **18**, 065401 (2016).
2. M. Šiler, L. Ornigotti, O. Brzobohatý, P. Jákl, A. Ryabov, V. Holubec, P. Zemánek, and R. Filip, Physical Review Letters **121**, (2018).

Orientational Quantum Revivals of Nanoscale Particles

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Testing the quantum superposition principle on macroscopic scales is a challenging task. While most future quantum superposition tests aim at observing center-of-mass interference [1,2], we propose an experimentally viable scheme for the observation of orientational quantum revivals, an interference effect of the orientational degrees of freedom, of nanoscale particles with a mass of 10^5 amu [3]. We discuss the effect of environmental decoherence [4,5] and the presence of an external torque on the rotational quantum dynamics of the particle.

References

[1] O. Romero-Isart, A. C. Pflanzer, F. Blaser, R. Kaltenbaek, N. Kiesel, M. Aspelmeyer, and J. I. Cirac, Phys. Rev. Lett. **107**, 020405 (2011).
[2] J. Bateman, S. Nimmrichter, K. Hornberger, and H. Ulbricht, Nat. Comm. **5**, 4788 (2014).
[3] B. A. Stickler, B. Papendell, S. Kuhn, B. Schrinski, J. Millen, M. Arndt, and K. Hornberger, New. J. Phys. **20**, 122001 (2018).
[4] B. A. Stickler, B. Papendell, and K. Hornberger, Phys. Rev. A **94**, 033828 (2016).
[5] B. Papendell, B. A. Stickler, and K. Hornberger, New. J. Phys. **19,** 122001 (2017).

Motional Dynamical Decoupling for Matter-Wave Interferometry

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Matter-wave interferometry provides a remarkably sensitive tool for probing minute forces and, potentially, the foundations of quantum physics by making use of interference between spatially separated matter waves. Furthering this development requires ever-increasing stability of the interferometer, typically achieved by improving its physical isolation from the environment. Here we introduce as an alternative strategy the concept of dynamical decoupling applied to spatial degrees of freedom of massive objects. We show that the superposed matter waves can be driven along paths in space that render their superposition resilient to many important sources of noise. As a concrete implementation, we present the case of matter-wave interferometers in a magnetic field gradient based on either levitated or free-falling nanodiamonds hosting a color center. Contrary to previous analyses, diamagnetic forces are not negligible in this type of interferometers and, if not acted upon lead to small separation distances that scale with the inverse of the magnetic field gradient. We show that our motional dynamical decoupling strategy renders the system immune to such limitations while continuing to protect its coherence from environmental influences, achieving a linear-in-time growth of the separation distance independent of the magnetic field gradient.

References

1. J. S. Pedernales, G. W. Morley, and M. B. Plenio, arXiv:1906.00835

Cooling silica nanoparticles in a Paul trap

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Nanoparticles levitated in Paul traps offer an isolated system with the potential for very low photon scattering making them a promising candidate for exploring macroscopic quantum mechanics. Experiments include cooling to the ground state [1] and creation of macroscopic superpositions [2]. Important to these investigations is to have precise control of the trapped nanoparticles and a good understanding of their dynamics. In this poster we demonstrate the effect of gas pressure and incident laser power on the trapped nanoparticle mass. Additionally, we have performed calibration of the COM (centre-of-mass) temperature and electro-optical feedback cooling of a COM mode to 14.5K. Finally, developments of the trap and detection are outlined to improve control of the particle and reduce the final cooled temperature.

References

[1] J. Millen, PRL **114**, 123602 (2015)
[2] M. Scala, PRL **111**, 180403 (2013)

Towards laser refrigeration of NV centres on the nanoscale

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Nitrogen vacancy (NV) centres in nano-diamonds are of considerable interest for exploring macroscopic quantum mechanics via a type of Ramsey interferometry utilising the single electron spin of the embedded NV [1]. While this idea is attractive, as it does not require strong centre-of-mass cooling, a central issue in its experimental realization is internal heating of the diamond due to the absorbed 532nm light that is used for spin polarisation. This problem intensifies when one tries to levitate the nano-diamond using optical fields, since the thermal interaction with the environment is reduced to the black body radiation of the nanoparticle.

A promising route to combat the deleterious effects of heating is the use of a laser-refrigeration via a nanocrystat [2] attached to the NV centre. So far, levitated rare-earth metal doped crystals on the nanoscale have shown to exhibit comparable cooling rates to bulk solid-state material refrigeration [3] where heat transfer from the crystal to the environment occurs by fluorescence without physical contact.

A major current obstacle in exploiting the fluorescence based refrigeration of levitated nanometre sized Yb3+:YLF crystals is getting the vacuum sufficiently low to reduce the interaction with the background gas. The poster will discuss feedback cooling implementations based on the redpitaya platform so that the particles can be refrigerated in high vacuum.

References

[1] M. Scala, M. S. Kim, G. W. Morley, P. F. Barker, and S. Bose, Phys. Rev. Lett. **111**, 180403 (2013)

[2] A. T. M. A. Rahman and P. F. Barker, Nature Photonics **11**, 634 (2017)

[3] D. V. Seletskiy, R. Epstein, and M. Sheik-Bahae, Reports on Progress in Physics **79**, 096401 (2016)

Large spatial Schrodinger cat using a levitated magnetic nanoparticle

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Quantum mechanics permits an object, however big, to be spatially delocalized in two different places at once. Despite being counter-intuitive and in direct conflict with our everyday experience, the superposition principle has been experimentally verified using neutrons, electrons, ions, and molecules[1]. The current record for the largest spatial superposition is 0.5m which was realized using a Bose-Einstein condensate of Rubidium atoms in an atomic fountain, while the heaviest object so far put into a superposition state is about $1x10^{-23}$ kg. However, a similar test using a mesoscopic object is still missing. A successful demonstration of such a state can testify collapse models, decoherence mechanisms, measurement hypothesis and the apparent conflict between relativity and quantum mechanics[1].

In this article, we propose an experimental scheme for creating a spatial Schrodinger cat by exploiting the superposition that naturally occurs when two potential wells are coupled together with a potential barrier in between them. Specifically, in magnetically ordered material such as ferromagnet and ferrimagnet with magnetocrystalline anisotropy different spin states are degenerate and are separated by an energy barrier[2]. In these systems, the ground state is the symmetric superposition of all-up and all-down spin states. Exploiting this naturally occurring spin superposition, and a magnetic field gradient, we propose a scheme for creating a spatial Schrodinger cat state. We show that the separation between the delocalized superposed states is significantly larger than the object involved in the superposition and can be as large as 10 micrometers. This large separation is crucial for the detection and verification of the non-classical states created.

References

1. M. Arndt and K. Hornberger, Nat. Phys. 10, 271 (2014).
2. D. D. Awschalom, D. P. DiVincenzo, and J. F. Smyth, Science 258, 414 (1992).

Stroboscopic Higher-Order Nonlinearity in Levitated Optomechanics

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Recent years have witnessed a rapid development of optomechanics, the field focusing on the interaction of radiation and matter via the radiation pressure. A plethora of experimental platforms has emerged demonstrating, among other achievements, ground state cooling of mechanical motion and entanglement of distant mechanical oscillators. A prospective field is the levitated optomechanics, in which the mechanical mode is defined by the motion of a subwavelength particle trapped in a potential provided by optical tweezer. An advantage of the levitated systems is, by design, the exceptional control over the motion of the particle granted by the tweezer. The tweezer allows tuning the potential felt by the particle over a wide range including nonlinear potentials beyond the harmonic one.

In this contribution we consider the stroboscopic application of a nonlinear potential (in particular, a cubic one) to the nanoparticle trapped in a harmonic potential. The mechanical states generated by the protocol clearly exhibit nonclassicality and the squeezing of a nonlinear combination of the particle's quadratures, proving the higher-order quantum nonlinearity and rendering them a useful resource for the mechanical quantum technology. We analyze the main sources of decoherence and estimate the achievable nonlinearities in the systems that are within reach.

Cavity Cooling of a Levitated Nanosphere by Coherent Scattering

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Cavity levitated optomechanics has gained a lot of interest in the previous years promising high mechanical quality factors and the access to room temperature quantum behavior [1]. Nonetheless cooling the mechanical motion of a levitated nanosphere to the ground state is yet to be achieved. Current limitations include co-trapping of the nanosphere by the cavity and particularly the laser phase noise [2].

There was significant progress in cavity cooling in recent years [3,4], where the nanosphere interacts with the cavity through a dispersive coupling. In this talk we present an alternative cooling scheme to the standard dispersive cavity cooling. We demonstrate 3D cavity cooling of the COM motion by coherent scattering, where the trapped nanoparticle is positioned inside an initially empty cavity mode. By locking the trapping light to the resonance of this mode, the light is scattered coherently into the cavity, introducing the optomechanical coupling. We demonstrate the positional and polarization dependence of the coupling with nanometer precision and achieve cooling of up to two orders of magnitude of the axial motion at a pressure of 10^-2 mbar with unprecedent high coupling rates. Furthermore we estimate that coupling of the laser phase noise is reduced compared to standard dispersive interaction, ultimately reducing residual heating. In the recoil limit (10^-7 mbar) we expect ground state cooling to be possible [5].

References

[1] Aspelmeyer et al. Rev. Mod. Phys., 86:1391-1452, 2014.

[2] Delic et al. (unpublished).

[3] Kiesel et al. Proceedings of the National Academy of Sciences, 110(35):14180-14185, 2013.

[4] Millen et al. Phys. Rev. Lett. 114, 123602, 2015

[5] Delic, Phys. Rev. Lett. 122, 123602

Thermometry of a single levitated nanodiamond

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The last Nobel Prize in physics has been awarded to A. Ashkin for his invention of optical tweezers. Through the numerous applications of optical tweezers, levitation of nanoparticles in vacuum has been lately at the center of an active research activity. Indeed, such a system is well suited for the observation of quantum effects at the mesoscale [1] and force metrology [2]. However, the use of intense laser field may heat up the particle reducing our chance to observe quantum effects [3], and altering its dynamics [4].
In that context, we measure the internal temperature of a levitated nanodiamond. This measure is based on the spin properties of the NV color centers hosted by the levitated nanodiamond. Indeed, the coupling between the spin and the diamond matrix provides a way to optically probe the nanodiamond internal temperature [5]. We thus compare the internal temperature to the center-of-mass motion temperature [4]. This work opens the way to the study of nanothermometry at the single particle level, as well as hybrid optomechanics where NV spins can be used to control the particle dynamics.

References

[1] Jain et al. Phy Rev Let **116**,243601 (2016)
[2] Hebestreit et al *Phys. Rev. Lett.* **121**, 063602 (2018)
[3] Kaltenbaek et al. EPJ Quant Tech **3**,5 (2016)
[4] J Millen et al. Nat Nano **9**,425 (2014)
[5] Thai M Hoang et al. Nat Comm **7**,12250 (2016)

Radiation reaction of a jiggling dipole in a quantum electromagnetic field

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We show how to derive a consistent quantum theory of radiation reaction of a non-relativistic point-dipole quantum oscillator by including the dynamical fluctuations of the position of the dipole. The proposed non-linear theory displays neither runaway solutions nor acausal behavior without requiring additional assumptions. Furthermore, we show that quantum (zero-point) fluctuations of the electromagnetic field are necessary to fulfil the second law of thermodynamics[1].

References

[1] A. E. Rubio López and O. Romero-Isart, arXiv:1905.06068 (15 May 2019).

Entangling optically levitated nanoparticles in a single cavity

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We propose an experimental scheme to prepare and detect the center-of-mass-entanglement of two optically levitated nanoparticles interacting via a high-Q cavity. The two nanoparticles are captured by two spatially separated tweezers and initially prepared close to their ground state. Pumping the cavity with a blue-detuned laser leads to two-mode-squeezing and entanglement of the two nanospheres. Once a Stokes photon in the output-mode of the cavity has been detected, the frequency of the laser is detuned to the red. An entanglement witness allows us to distinguish classical from quantum correlations of the particles, using the photon statistics of an anti-Stokes photon. We estimate the efficiency of the entanglement creation for realistic parameters.

Rotational friction and thermalization of quantum rigid rotors

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We present the general Markovian quantum master equation describing rotational decoherence, friction, diffusion, and thermalization of a rigid rotor in contact with a thermal environment [1]. The master equation describes thermalization toward a Gibbs-like rotation state and gives rise to the rotational Fokker-Planck equation in its semiclassical limit. Its adequacy and applicability is demonstrated by studying the thermalization dynamics of the linear and the planar top.

Possible applications include experimental tests of the quantum superposition principle involving the rotational degree of freedom [2,3], molecular quantum experiments in the field of ultracold chemistry [4], as well as the assessment of the thermodynamic efficiency of quantum rotor heat engines [5].

References

[1] B. A. Stickler, B. Schrinski, and K. Hornberger, Phys. Rev. Lett. **121**, 040401 (2018)

[2] B. A. Stickler, B. Papendell, S. Kuhn, B. Schrinski, J. Millen, M. Arndt, and K. Hornberger, New. J. Phys. **20**, 122001 (2018)

[3] B. Schrinski, B. A. Stickler, and K. Hornberger, J. Opt. Soc. Am. B **34**, C1 (2017)

[4] S. A. Moses, J. P. Covey, M. T. Miecnikowski, D. S. Jin, and J. Ye, Nat. Phys. **13**, 13 (2017)

[5] A. Roulet, S. Nimmrichter, J. M. Arrazola, S. Seah, and V. Scarani, Phys. Rev. E **95**, 062131 (2017)

Parametric Feedback Cooling of Rigid Body Nanodumbbells in Levitated Optomechanics

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We theoretically investigate the rigid body dynamics of an optically levitated nanodumbbell under parametric feedback cooling and provide a simplified model for describing the motion. Differing from previous studies, the spin of the nanoparticle about its symmetry axis is considered nonnegligible. Simulations reveal that standard parametric feedback cooling can extract energy from two of the five rotational degrees of freedom when the nanoparticle is levitated using a linearly polarized laser beam. The dynamics after feedback cooling are characterized by a normal mode describing precession about the laser polarization axis together with spin about the nanoparticle's symmetry axis. Cooling the remaining mode requires an asymmetry in the two librational frequencies associated with the motion about the polarization axis as well as information about the two frequencies of rotation about the polarization axis. Introducing an asymmetric potential allows full cooling of the librational coordinates if the frequencies of both are used in the feedback modulation and is an avenue for entering the librational quantum regime. The asymmetry in the potential needs to be large enough for practical cooling times as the cooling rate of the system depends nonlinearly on the degree of asymmetry, a condition that is easily achieved experimentally.

References

[1] T. Seberson and F. Robicheaux, Phys. Rev. A **99**, 013821 (2019)

Analysis on non-linear behavior of optically levitated particle via ensemble averaged transient dynamics

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Optically levitated nanoparticles in vacuum have gained much attention for their ultrasensitivity to weak forces [1] as well as for the potential for investigations in the field of quantum physics. In contrast to other nano- and micromechanical oscillators, the optically trapped nanoparticle in vacuum has no clamping losses, its motion is influenced only by a laser beam and its potential profile and, therefore, the mechanical quality factor of such oscillator is very high. In majority of studies the optical restoring force is considered harmonic, i.e. the force is directly proportional to the displacement from the center of the optical trap. However, in vacuum the anharmonicity of the optical potential starts to play an important role [2]. This can be observed in power spectrum density profile where the oscillation peak is broadened and asymmetric, see Fig. 1a. In this contribution we demonstrate a novel method of analysis of ensemble averaged trajectories which allows us to study the transient dynamics of the non-linear system for various initial conditions. An example is shown in Fig. 1b which depicts evolution of ensemble averaged particle trajectories for various initial conditions and pressures. Our method allows us to obtain parameters of the levitated oscillators, such as trap stiffness, anharmonicity, damping, and temperature directly from the recorded particle motion without the need for any kind of external driving or modification of the experimental system.

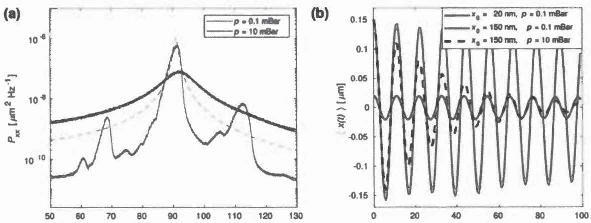

Figure 1: (a) Power spectral density of optically levitated particle at pressures 10 and 0.1 mBar. Dashed curves show the fit by Lorentzian profiles. (b) Averaged trajectories <*x(t)*> obtained by averaging trajectories starting at the same point in the phase space for different initial amplitudes x_0 at pressure 0.1 mBar (solid) and 10 mBar (dashed).

References

[1] J. Gieseler, et al., Phys. Rev. Lett. **109**, 103603 (2012)
[2] J. Gieseler, et al., Nat. Phys. **9**, 806 (2013)

Nonlinear dynamics of optically rotated nanorods in a high Reynolds number environment

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We present the motion analysis of a nanorod driven by a rotating optical field in a high Reynolds number environment. In contrast to low Reynolds number environments [1] [2], its nonlinear motion is more complex on account of unneglectable inertial terms. Several regimes of the particle motion are established by nonlinear dynamics. Fig. 1(a) shows a focus on conditions that optical field frequencies are lower than the critical frequency (i.e. $\Omega < \Omega_c$), which means that $\phi = \arcsin(\Omega/\Omega_c)$ and $\dot{\phi} = 0$ are the only stable solutions of the equation of motion. And $\phi = 2(\Omega t - \theta)$, in which θ is the rotation angle of the nanorod. So we can obtain that the rotation rate of the nanorod is $\dot{\theta} = \Omega$. The nanorod rotates synchronously with optical field, but lags in phase by $\phi/2$. It is known as 'phase-locked' rotation, which shows a great prospect in ultra-high precision measurement and high-Q system. In Fig.1(b), there is no solution to the equation of motion, so the nanorod's motion is periodic.

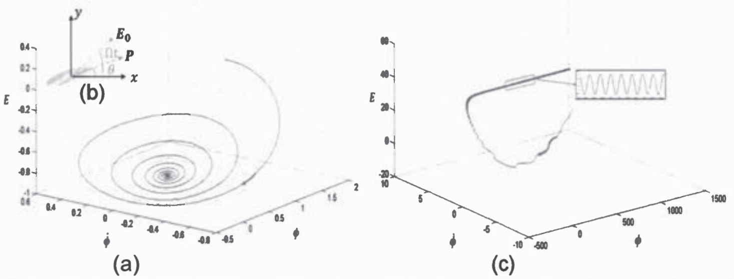

Figure 1. (a) is the 3D phase portrait of the equation of motion of a nanorod at $\Omega < \Omega_c$. $\dot{\phi}$ is the first derivative of ϕ versus time. E is the total energy of the nanorod, which is the sum of its kinetic energy and potential energy. The inset (b) is the relative positon of the incident optical field and the induced dipole moment. (c) is the 3D phase portrait of the equation of motion of a nanorod at $\Omega \geq \Omega_c$. And the inset shows details of the red frame.

References

[1] W. Andrew Shelton, Keith D. Bonin and Thad G. Walker, Phys. Rev. E **71**, 036204 (2005).

[2] A. Cēbers and M. Ozols, Phys. Rev. E **73**, 021505 (2006).

Optical binding of microparticles levitated in counter-propagating beams optical trap in vacuum

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Force interaction between mesoscopic particles levitated in vacuum is essential for realization of a large-scale array of coupled particles in an underdamped environment [1,2]. Such optomechanical array is an ideal playground for study of phonon dynamics and energy transport in it. In this contribution we demonstrate the optical binding [3] between two microparticles optically trapped in counter-propagating laser beams in vacuum (Fig. 1a). We investigate the binding phenomena in both the standing wave (SW) and the crossed polarizations (CRP) configuration. Analyzing the Power Spectral Density functions of the particles' motion (see Fig. 1d,e) we show that the collective behavior can be described in terms of the normal modes of coupled oscillators - the center-of-mass (COM, Fig. 1b) and the relative positions (BR, Fig. 1c) of the two-particle system.

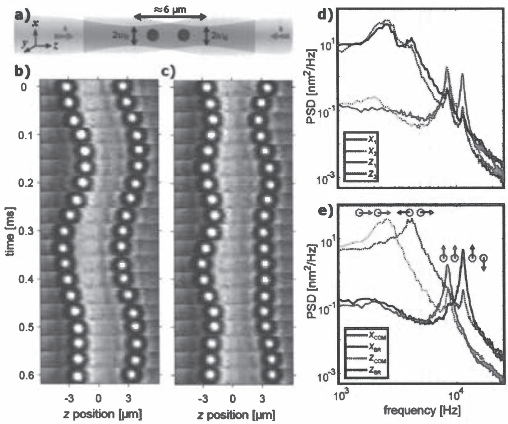

Figure 1: (a) Experimental arrangement. (b,c) Series of videomicroscopy images depicting the COM mode (b) and the BR mode (c) of oscillation. (d) Power spectral density of individual bound particles at pressure 10 mBar. (e) Power spectral density of collective modes of motion.

References

[1] Y. Arita, et al., Optica **5**, 910 (2018)
[2] D. S. Bykov, et al., Light Sci. Appl. **7**, 22 (2018)
[3] K. Dholakia and P. Zemánek, Rev. Mod. Phys. **82**, 1767 (2010).

Detection of anisotropic particles in levitated optomechanics

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We discuss the detection of an anisotropic particle trapped by an elliptically polarized focused Gaussian laser beam. We obtain the full rotational and translational dynamics, as well as, the measured photo-current in a general-dyne detection. As an example, we discuss a toy model of homodyne detection, which captures the main features typically found in experimental setups [1].

We investigate experimentally the dynamics of a non-spherical levitated nanoparticle in vacuum. In addition to translation and rotation motion, we observe the light torque-induced precession and nutation of the trapped particle. We provide a theoretical model, which we numerically simulate and from which we derive approximate expressions for the motional frequencies. Both the simulation and approximate expressions, we find in good agreement with experiments. We measure a torque of $1.9 \pm 0.5 \times 10^{-23}$ Nm at 1×10^{-1} mbar, with an estimated torque sensitivity of $3.6 \pm 1.1 \times 10^{-31}$ $\mathrm{Nm/Hz^{1/2}}$ at 1×10^{-7} mbar [2].

References

[1] Toroš, M., Rashid, M. and Ulbricht, H., 2018. Detection of anisotropic particles in levitated optomechanics. Physical Review A, 98(5), p.053803.

[2] Rashid, M., Toroš, M., Setter, A. and Ulbricht, H., 2018. Precession motion in levitated optomechanics. Physical review letters, 121(25), p.253601.

Towards microcavity cooling of nanoparticles

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Cavity cooling of nanoparticles is an interesting tool for preparing mesoscopic matter for applications in advanced quantum experiments and novel sensors. While cooling of particles in the 10^8 – 10^{10} amu range has already been successfully demonstrated [1-5], novel quantum interference and sensing experiments target objects in the 10^6 – 10^7 amu range. Even though the polarizability of these objects is smaller, sufficient dispersive coupling to the light field can be achieved in microcavities with a small mode volume [6]. To achieve mode volumes of the order of 1 pL, we explore chip-based high-finesse microcavities in pristine silicon [7]. With radii of curvature in the range of 140 – 280 µm and finesses as high as 500 000, they pave the way for cavity cooling in the 10^7 amu range. We present advances in the detection and capture of nanoparticles in those microcavities and our prospects for cooling.

References

[1] P. Asenbaum, S. Kuhn, S. Nimmrichter, U. Sezer, M. Arndt, Nat. Commun. **4**, 2743 (2013)
[2] P. Z. G. Fonseca, E. B. Aranas, J. Millen, T. S. Monteiro, P. F. Barker, Phys. Rev. Lett. **117**, 173602 (2016)
[3] J. Vovrosh, M. Rashid, D. Hempston, J. Bateman, M. Paternostro, H. Ulbricht, J. Opt. Soc. Am. B **34**, 1421 (2017)
[4] U. Delić, M. Reisenbauer, D. Grass, N. Kiesel, V. Vuletić, M. Aspelmeyer, Phys. Rev. Lett. **122**, 123602 (2019)
[5] F. Tebbenjohanns, M. Frimmer, A. Militaru, V. Jain, L. Novotny, Phys. Rev. Lett. **122**, 223601 (2019)
[6] S. Kuhn, G. Wachter, F.-F. Wieser, J. Millen, M. Schneider, J. Schalko, U. Schmid, M. Trupke, M. Arndt, Appl. Phys. Lett. **111**, 253107 (2017)
[7] G. Wachter, S. Kuhn, S. Minniberger, C. Salter, P. Asenbaum, J. Millen, M. Schneider, J. Schalko, U. Schmid, A. Felgner, D. Hüser, M. Arndt, M. Trupke, Light-Sci. Appl. **8**, 37 (2019)

Rotational Feedback Cooling of Dielectric Nanorods

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In nano-optomechanics with free and levitated nanoparticles, non-spherical objects have attracted increasing interest because of their additional degrees of freedom, which provide a new handle for their manipulation and the observation of new phenomena.

While center of mass cooling is expected to open new avenues for matter-wave interferometry [1, 2] and tests of the quantum superposition principle, rotational cooling shall lead to quantum superpositions in rotation and quantum revivals [4], with applications in extremely sensitive torque sensing.

An essential ingredient towards these goals is cavity cooling, which theory predicts to achieve even a 5D ground state cooling, along 3 center of mass directions and two rotational axes [5].

Optical control of the rotational motion has recently been demonstrated with silicon nanorods [6, 7], but so far, the trapping of the rods was limited to pressures above 1 mbar, where the buffer gas damps instabilities of the trapped rod. This is a severe limit for cavity cooling, particle manipulation and metrology.

To overcome this limit, we here discuss our advances in feedback cooling of the translational degrees of freedom and rotational feedback cooling of the two librational motions, via parametric modulation of the trapping intensity and how this influences the capability to trap the rods in different pressure regimes.

References

[1] Arndt, M. and K. Hornberger, *Insight review: Testing the limits of quantum mechanical superpositions.* Nature Physics, 2014. 10: p. 271-277.

[2] Bateman, J., et al., *Near-field interferometry of a free-falling nanoparticle from a point-like source.* Nature Communications, 2014. 5: p. 4788.

[3] Kuhn, Stefan, et al., *Optically driven ultra-stable nanomechanical rotor*, Nature communications 8.1 (2017): 1670.

[4] Stickler, B.A., et al., *Probing macroscopic quantum superpositions with nanorotors.* New Journal of Physics, 2018. 20(12): p. 122001.

[5] Stickler, Benjamin A., et al. *Rotranslational cavity cooling of dielectric rods and disks*, Physical Review A 94.3 (2016) 033818.

[6] Kuhn, S., et al., *Full rotational control of levitated silicon nanorods.* Optica, 2017. 4(3): p. 356-360.

[7] Kuhn, Stefan, et al., *Optically driven ultra-stable nanomechanical rotor*, Nature communications 8.1 (2017): 1670.

Cavity-Based 3D Cooling of a Levitated Nanoparticle via Coherent Scattering

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We experimentally realize [1] cavity cooling of all three translational degrees of motion of a levitated nanoparticle in vacuum. The particle is trapped by a cavity-independent optical tweezer and coherently scatters tweezer light into the blue detuned cavity mode. For vacuum pressures around 10^{-5} mbar, minimal temperatures along the cavity axis in the mK regime are observed. Simultaneously, the center-of-mass (COM) motion along the other two spatial directions is cooled to minimal temperatures of a few hundred mK. Measuring temperatures and damping rates as the pressure is varied, we find that the cooling efficiencies depend on the particle position within the intracavity standing wave. This data and the behaviour of the COM temperatures as functions of cavity detuning and tweezer power are consistent with a theoretical analysis [2] of the experiment. We discuss experimental limits and opportunities of our approach.

References

[1] D. Windey, **Phys. Rev. Lett. 122**, 123601 (2019)
[2] C. Gonzalez-Ballestero, **arXiv:1902.01282** (2019)

High frequency gravitational wave detection with levitated nano objects.

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We present updated theoretical results for detecting gravitational waves with a levitated nano object optically suspended within a cavity as a complementary instrument to experiments like LIGO. Our experimental proposal is designed to detect gravitational waves in the 10's to 100's of Kilohertz bandwidth on a tabletop scale. The planned experimental setup is detailed and several optimizations to the proposal are outlined. Finally, the proposal is placed within the context of newly analysed predicted sources within such a frequency band.

Dynamic Simulation of Optically Levitated Rotating Particle in High Vacuum

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Optically levitated high-speed rotating nanoscale particles in high vacuum can be treated as high quality mechanical oscillators to achieve torque sensing. Experiments showed that in high vacuum, a circularly polarized laser beam can levitate and control a microsphere to rotate at rate above GHz. Optical levitated nano-particles in high vacuum can be regarded as a high speed rotor. Former studies have shown that laser levitated micron-sized spheres in vacuum can perform precise measurements of forces and torque[1-3], but most of them were based on the torsional frequency. By considering ellipsoid particles, we expect to sense the variation of external torque via detecting rotation speed and nutation angle.

The precision measurement based on optical levitated rotator requires the thoroughly analysis of particle's state of motion, including the variation of Euler angles due to the change of external torque. We present the simulation of particle's dynamic motion and analysis the feasibility of external torque measurement with rotating particles in optical tweezer.

Here we choose ellipsoidal SiO_2 particle with major axis of 5μm and minor axis of 4μm as simulation object and set T=300K, P=0.04mbar. We also learn that circularly polarized laser at beam power P=400mW will bring torque $M=1.42*10^{-13}$N-m.

From the simulation, we can obtain several conclusions. First, the relaxation time of rate in high vacuum is less than 0.0001s, which requires high bandwidth We also notice that when applying external torque, the angular velocity changes sharply(10^7Hz). In future researches, we will consider use simulation objects of different shapes and external environment factor and increase sensitivity.

References

[1] Jonghoon A , Zhujing X , Jaehoon B , et al. Optically Levitated Nanodumbbell Torsion Balance and GHz Nanomechanical Rotor[J]. Physical Review Letters, 2018, 121(3):033603-.

[2] Fonseca P Z, Aranas E B, Millen J, et al. Nonlinear Dynamics and Strong Cavity Cooling of Levitated Nanoparticles[J]. Physical Review Letters, 2016, 117(17):173602.

[3] [3] Coppock J E, Nagornykh P, Murphy J P J, et al. A dual-trap system for the study of charged rotating graphene nanoplatelets in high vacuum[J]. Journal of the Optical Society of America B, 2017, 34(6).

Microsphere cooling in optical tweezers in air based on FPGA controller

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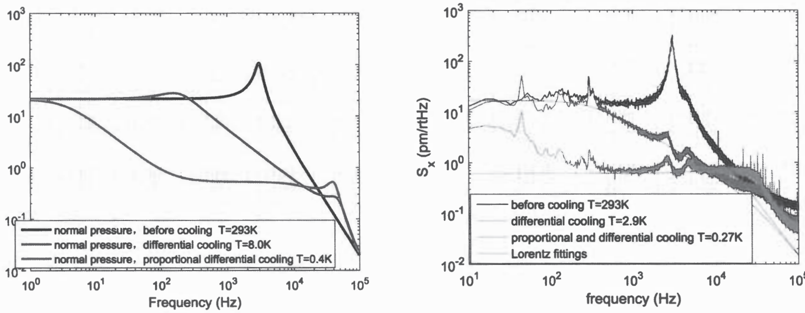
A set of optical tweezers system in air based on FPGA controller has been built for weak forces measurement and fundamental physics research. The influence of the alignment error of two counter-propagating beams and the noise of the laser source on the accuracy and stability of the system are analyzed. We have deduced a relatively precise PID control theoretical model for the microsphere cooling considering the hysteresis of the feedback phase and noises in optics and electronics. The equivalent temperature of a 10μm SiO_2 microsphere is cooled from room temperature to 0.27K under normal atmospheric condition. Fig. 1(a) shows the displacement spectrum of the centroid of the microsphere $S_x$simulated according to the Langevin's equation [1]. They conform to the Lorentz curve as the theory predicts while S_x rises slightly among the frequency regions where feedback phase reverses. In Fig. 1(b), the equivalent temperatures estimated by the displacement variance after cooling can achieve 0.27K in air based on proportional and differential cooling method.



(a) (b)

Figure 1. (a)Simulation. Black curve indicates displacement spectrum before cooling. Situation of the differential cooling is expressed by blue line and the purple one represents the proportional and differential cooling. (b) Experiment. All displacement spectrums are fitted with cyan Lorentz linetypes.

References

[1] Li T, Nature Physics **7**, 527-530(2011), Fundamental tests of physics with optically trapped microspheres