Room temperature optomechanical squeezing

Nancy Aggarwal

Northwestern University

The precision of current LIGO and VIRGO detectors is limited by the quantum-mechanical fluctuations of the electromagnetic field. Squeezed light can lower this quantum noise, furthering the astrophysical reach of GW detectors. I will describe a new way of creating squeezed light - optomechanical squeezing. Developing technologies for wavelength-independent squeezing allows for ubiquitous use in measurements affected by quantum uncertainty. This requires building systems that can exhibit quantum behavior at room temperature despite being coupled to a thermal environment. I will show that it is indeed possible to design a macroscopic, room-temperature system that has low enough Brownian motion so as to exhibit measureable quantum effects [1] [2]. If time permits, I will present a direct correlation-based approach to measure squeezing, obviating the need for calibration [2].

[1] https://www.nature.com/articles/s41567-020-0877-x

[2]https://www.nature.com/articles/s41586-019-1051-4?platform=hootsuite

Universal matter-wave interferometry: opportunity and challenges in probing quantum physics at the interface to gravity

Markus Arndt

University of Vienna

Quantum physics and gravity theory have both already celebrated their first centenary and yet, they have been neither united in a common framework, nor have they been seriously challenged experimentally. Both have been beautifully confirmed wherever they were tested - individually. It is therefore natural to ask, if one can devise experiments that can probe quantum physics at the interface to gravity to find a hint for any non-trivial mutual influence that may eventually force us do modify one or the other or both.

Numerous ideas have been proposed in the literature, how the quantum nature of space-time could influence matter-waves or how delocalized matter itself would warp space-time to back-act on its very quantum nature. Many models of space-time effects in quantum experiments suggest that the effects should scale with the mass of the delocalized object, often specifically with m^2.

This reasoning motivates a new line of research in our group to develop sources, detectors and interferometers for universal matter-wave interferometry with clusters whose mass, energy, material composition and internal complexity we can tune over many orders of magnitude and with a high degree of control. I will discuss the experimental state of the art and put the proposed experiments into context with the challenges in the field.

Gravitational coupling of microscopic source masses: challenges for future quantum Cavendish experiments

Markus Aspelmeyer

University of Vienna

No experiment today provides evidence that gravity requires a quantum description. It has been suggested that one can at least exclude the possibility for semiclassical gravity by performing an experiment whose outcome cannot be explained by a purely classical mass configuration. It turns out that such "quantum Cavendish" experiments are challenging, to say the least. I highlight some of the practical aspects of this challenge using the concrete example of our recent measurement of the gravitational field of a 1mm gold sphere [1], the smallest source mass to date in table-top gravity experiments.

[1] Westphal et al., Nature 591, 225 (2021)

Charged levitated nano-oscillators for testing macroscopic quantum mechanics

P. Barker[1], A. Pontin1, T. Penny[1], N. Bullier[1], M. Toros[1], H. Ulbricht[2], M. Drewsen[3], M. Bazzi[4], C. Curceanu[4]

1Department of Physics and Astronomy, University College London, London, United Kingdom

2Department of Physics and Astronomy, University of Southampton, Southampton, United Kingdom

3Department of Physics and Astronomy, Aarhus University, Aarhus, Denmark

4INFN, Laboratori Nazionali di Frascati, Frascati, Italy

The Paul trap is a well-developed and highly successful tool for exploring quantum mechanics with atomic ions, while more recently it has been considered as a platform for exploring quantum mechanics in the macroscopic regime.

In this presentation, I will describe our work which has been developing this system as a low noise quantum-optomechanical system for testing quantum mechanics using charged levitated nanoparticles. I will outline cavity cooling and feedback cooling experiments that we have undertaken for controlling the motion of these single nanoparticle oscillators. I will also discuss initial experiments that have placed bounds on dissipative collapse models and describe future experiments within the TEQ programme that aim to place stringent bounds on collapse models. Lastly, I will discuss the applicability of this platform for creating and evidencing quantum superpositions and for induced entanglement experiments.

First search for new long range forces at the micron scale using optically levitated microspheres

Chas Blakemore

Stanford University

I will discuss a search for non-Newtonian forces that couple to mass, with a characteristic scale of ${\sim}10~\mu$m, using an optically levitated microsphere as a precision force sensor. A silica microsphere trapped in an upward-propagating, single-beam, optical tweezer is utilized to probe for interactions sourced from a nanofabricated attractor mass with a density modulation brought into close proximity to the microsphere and driven along the axis of periodic density in order to excite an oscillating response. We obtain force sensitivity of ${\lesssim}10^{-16}~\rm{N}/\sqrt{\rm{Hz}}$. Separately searching for attractive and repulsive forces results in the constraint on a new Yukawa interaction of $|\alpha| \gtrsim 10^8$ for $\lambda > 10~\mu$m. This is the first test of the inverse-square law using an optically levitated test mass of dimensions comparable to λ, a complementary method subject to a different set of system effects compared to more established techniques. Near-term improvements to the apparatus and experimental technique are expected to push the sensitivity into unexplored parameter space.

Quantum Nature of Gravity in the Lab: Assumptions, Implementation and Applications on the Way

Sougato Bose

University College London

There is no empirical evidence yet as to "whether" gravity has a quantum mechanical origin. Motivated by this, I will present a feasible idea for testing the quantum origin of the Newtonian interaction based on the simple fact that two objects cannot be entangled without a quantum mediator. I will show that despite its weakness, gravity can detectably entangle two adjacent micron sized test masses held in quantum superpositions even when they are placed far apart enough to keep Casimir-Polder forces at bay. A prescription for witnessing this entanglement through spin correlations is also provided. Further, I clarify the assumptions underpinning the above proposal such as our reasonable definition of "classicality", as well as relativistic causality. We note a few ways to address principal practical challenges: Decoherence, Screening EM forces and Inertial noise reduction. I will also describe how unprecedented compact sensors for classical gravity (including meter scale sensors for low frequency gravitational waves) will arise on the way to the above grand goal.

Theory implications from tabletop gravity experiments

Daniel Carney

Lawrence Berkley lab

Experiments involving massive, quantum-mechanical systems can be used to test a number of proposals for the quantum behavior of gravity at energy densities well below the Planck scale. I'll give a few examples from models which go beyond the usual effective quantum field theory picture, and some more detailed comments on graviton interpretations.

Simple experiments to probe parity violation in Gravitation, and their theoretical implications.

N. D. Hari Dass

Institute of Mathematical Sciences - Chennai

In 1975 I had proposed some very simple experiments to probe discrete symmetry violations in gravitation. The experiment in itself was a sort of gravitational analog of the famous Ramsey expt for measuring EDM.

Subsequently, several experimental groups, even to this day, are improving the precisions of the proposed experiment. The theoretical implications of a positive outcome for such tests are enormous. Among them would be the breakdown of Einstein's general relativity theory. I will also discuss some future possibilities for experiments.

References:

1. N.D. Hari Dass, Tests for C,P,T violations in gravitation, Phys.Rev.Lett. 36 No. 8 393 (1976).

2. N.D. Hari Dass, Experimental tests for some quantum effects in gravitation, Ann. Phy. 107 337 (1977).

3. N.D. Hari Dass, Cold atoms for testing quantum mechanics, and, parity violation in gravitation, arXiv:9908085v1[quant-ph].

Magneto-Gravitational Trapping of SiC Particles Containing Si-Vacancy Centers

Brian D’ Urso

Montana University

Magneto-gravitational traps use the repulsion of diamagnetic materials by magnetic fields combined with the Earth's gravity to create a weak trap for micrometer-scale diamagnetic particles. A single particle levitated in this trap oscillates harmonically in three dimensions and its position can be measured optically. We have previously demonstrated feedback cooling of a trapped particle using radiation pressure from a second light source, but the low frequencies of oscillation appear to make quantum behavior unreachable, at least on long time scales. However, two additional techniques may yet enable quantum behavior in these traps. First, replacing the usual trapped object, a silica microsphere, with a silicon carbide particle introduces the possibility of coupling the mechanical motion with spins associated with defect states of the silicon carbide. Since the coherence times of these spins are typically short compared to the particle oscillation periods, a second system modification is required: optical measurements of the particle position on time scales short compared to the oscillation period of the motion, making the behavior approach that of a free particle. We report on progress towards these approaches.

Matter-wave interferometers on the atom chip

Ron Folman

Ben Gurion University

Matter-wave interferometry provides an excellent tool for fundamental studies as well as technological applications. In our group, several interferometry experiments have been done with a BEC on an atom chip [1] examining different effects. For example, we studied fluctuations in the nearby environment by an interference of atoms trapped in a magnetic lattice very close (5μm) to a room temperature surface [2,3]. We realized a new interferometry scheme of self-interfering clocks and showed, in a proof-of-principle experiment, how this could probe the interplay of QM and GR [4]. We also described a rule for "clock complementarity", which we deduce theoretically and verify experimentally [5]. In the clock interferometer, we have observed phase jumps due to the existence of a geometric phase [6]. Furthermore, we realized Stern-Gerlach interferometry [7-10] despite several theoretical works which have shown over the years that fundamental barriers exist.

I will give a brief description of the advantages of the atom chip, and will then describe several of the interferometric schemes, and their connection to issues such as environmentally and gravitationally (red-shift) induced decoherence, as well as loss of coherence due to interferometer imprecision (the humpty-dumpty effect). I will conclude with an outlook concerning ideas for possible tests of exotic physics such as quantum gravity, and mention several speculations which we hope to examine in the future.

[1] M. Keil et al., "Fifteen years of cold matter on the atom chip: Promise, realizations and prospects", Journal of Modern Optics 63, 1840 (2016).

[2] S. Zhou et al., "Robust spatial coherence 5□m from a room temperature atom-chip", Phys. Rev. A 93, 063615 (2016).

[3] Y. Japha et al., "Suppression and enhancement of decoherence in an atomic Josephson junction", New J. Phys. 18, 055008 (2016).

[4] Y. Margalit et al., "A self-interfering clock as a 'which path' witness", Science 349, 1205 (2015).

[5] Z. Zhou et al., "Clock complementarity in the context of general relativity", Classical and Quantum Gravity 35, 185003 (2018).

[6] Zhifan Zhou, Yair Margalit, Samuel Moukouri, Yigal Meir, and Ron Folman "An experimental test of the geodesic rule proposition for the non-cyclic geometric phase", Science Advances 6, eaay8345 (2020).

[7] S. Machluf et al., "Coherent Stern-Gerlach momentum splitting on an atom chip", Nature Communications 4, 2424 (2013).

[8] Y. Margalit et al., “Analysis of a high-stability Stern-Gerlach spatial fringe interferometer”, New J. Phys. 21, 073040 (2019).

[9] O. Amit, Y. Margalit, O. Dobkowski, Z. Zhou, Y. Japha, M. Zimmermann, M. A. Efremov, F. A. Narducci, E. M. Rasel, W. P. Schleich, R. Folman. “T3 Stern-Gerlach matter-wave interferometer”, Phys. Rev. Lett. 123, 083601 (2019).

[10] Mark Keil, Shimon Machluf, Yair Margalit, Zhifan Zhou, Omer Amit, Or Dobkowski, Yonathan Japha, Samuel Moukouri, Daniel Rohrlich, Zina Binstock, Yaniv Bar-Haim, Menachem Givon, David Groswasser, Yigal Meir, Ron Folman, “Stern-Gerlach Interferometry with the Atom Chip”, Invited review paper, to appear in a book in honor of Otto Stern, https://arxiv.org/abs/2009.08112 (2020).

One-Particle Quantum Cyclotron

Gerald Gabriele

Northwestern University

A one-lepton quantum cyclotron is realized at cryogenic temperatures below 0.1 K, within a vacuum better than 10^{-17 Torr. Measurements of the electron and positron magnetic moments (in Bohr magnetons) are underway with the goal of determining these moments to 3 parts in 10^{14}. These measurements will be the most accurate measurements ever made of any property of an elementary particle. They will be used to test the standard model's most precise prediction, will provide the most sensitive test of the fundamental CPT symmetry invariance of the Standard Model with leptons, will make it possible to make better muon magnetic moment measurements, and will provide the most accurate determination of the fine structure constant. A new method to circumvent detection backaction will be employed, along with the incorporation of quantum limited detection that is in addition to the quantum nondemolition methods already employed.

Looking for “fifth forces”, dark matter, and quantum gravity with optomechanical sensors

Andrew Geraci

Northwestern University

We normally think of large accelerators and massive detectors when we consider the frontiers of elementary particle physics, pushing to understand the universe at higher and higher energy scales. However, several tabletop low-energy experiments are positioned to discover a wide range of new physics beyond the Standard model of particle physics, where feeble interactions require precision measurements rather than high energies. In high vacuum, optically levitated dielectric objects achieve excellent decoupling from their environment, making force sensing at the zeptonewton level (10-21 N) achievable. In this talk I will describe our work towards using these and other optomechanical sensors to search for quantum effects related to gravity, gravitational waves, and dark matter.

Terrestrial gravity fluctuations in GW detectors

Jan Harms

Gran Sasso Institute

The large-scale gravitational-wave (GW) detectors Virgo and LIGO have achieved unprecedented sensitivities in relative position measurements between suspended test masses. The tremendous challenge to identify and suppress all sorts of environmental couplings was hardly anticipated in its full scale when Virgo and LIGO were first conceived. The reduction of environmental noise and noises created by the control systems suppressing the environmental noise is a major challenge of detector commissioning and sensitivity advance today. Among the many environmental couplings, direct gravitational coupling between test masses and their environment stands out as a nearly insurmountable obstacle to extend the observation band of ground-based detectors to frequencies below 10Hz. In this talk, I will review the various sources of terrestrial gravity noise and outline the mitigation strategies envisioned by GW scientists.

Measuring the higher-order phonon statistics in a nanogram volume of superfluid helium

Jack Harris

Yale University

We detect the individual sideband photons produced by an optomechanical device consisting of a nanogram of superfluid helium confined in a Fabry-Perot cavity. We use the photon-counting data to probe the phonon-phonon correlations (up to fourth order, and for both normal-ordering and anti-normal-ordering) in a single acoustic mode of the superfluid. The data is consistent the assumption that the acoustic mode is in a thermal state with mean phonon number ~ 1. We also use sideband-photon counting to show that the acoustic mode can be driven to a coherent amplitude corresponding to several thousand phonons with no decrease in the acoustic state's purity. We will discuss the application of such high-purity, high-amplitude states to various tests of quantum gravity

Quantum rotations of nanoparticles

Benjamin Stickler

University of Duisburg-Essen

The non-linearity and anharmonicity of rigid body rotations gives rise to pronounced quantum interference effects with no analogue in the body's centre-of-mass motion [1]. This talk will briefly review two such effects, orientational quantum revivals [2] and the quantum tennis racket effect [3], and discuss how elliptic coherent scattering cooling [4] opens the door to rotational quantum experiments with nanoscale particles and rotational tests of collapse models [5].

[1] Stickler, Hornberger, and Kim, arXiv: 2102.00992 (2021).
[2] Stickler, Papendell, Kuhn, Millen, Arndt, and Hornberger, New J. Phys. 20, 122001 (2018).
[3] Ma, Khosla, Stickler, and Kim, Phys. Rev. Lett. 125, 053604 (2020).
[4] Schäfer, Rudolph, Hornberger, and Stickler, Phys. Rev. Lett. 126, 163603 (2021).
[5] Schrinski, Stickler, and Hornberger, J. Opt. Soc. Am. B 34, C1 (2017).

Probing gravity nonlocally with macroscopically delocalized atom interferometers

Timothy Kovachy

Northwestern University

Atom interferometers in which atoms are delocalized over macroscopic distances can serve as highly sensitive probes of gravity. Such atom interferometers have recently enabled the first observation of gravitational tidal forces across a single particle's wavefunction. In this regime, each atom experiences gravity in a fundamentally nonlocal manner. I will discuss the conceptual significance of this work and its ramifications for certain proposed models of gravity-related decoherence. Moreover, I will describe new experimental efforts to extend this work to even larger spatial delocalizations.

Effects of space-time fluctuations on quantum systems

Claus Laemmerzahl

University of Bremen

Ultrasensitive torque detection with an optically levitated nanoparticle

Tongcang Li

Purdue University

Optical tweezers provide a non-contact method to manipulate microscopic objects and have many critical applications in precision measurements. Recently, we developed an optically levitated Cavendish torsion balance for quantum-limited torque and force sensing. We have optically levitated nanoparticles in a vacuum and driven them to rotate up to 300 billion rpm (5 GHz). Using a levitated nanoparticle in a vacuum, we demonstrated ultrasensitive torque detection with a sensitivity several orders higher than the former record. This system will be promising to study quantum friction, Casimir torque, and gravity at short distances.

Towards testing quantum gravity using the full-loop Stern-Gerlach interferometer

Yair Margalit

MIT

Matter-wave interferometry using nano-particles has been suggested for various exotic experiments, from detection of gravitational waves to testing of the quantum nature of gravity. However, extending the use of state of the art laser-pulse atom interferometers to nano-particles is severely restricted due to the lack of discrete energy transitions which are used in atoms. Recently, the full-loop Stern-Gerlach interferometer has been suggested as a tool for realizing interferometry of nano-particles embedded with a single spin. In my talk, I will describe the first realization of a full-loop Stern-Gerlach interferometer for single atoms, and discuss the possibility of using this novel setup to realize an interferometer for macroscopic objects such as nano-diamonds. Such a scheme, which uses population fringes as its signal, has several advantages over schemes which use spatial interference patterns as a signal.

The design and use of Stern-Gerlach interferometry for Gravitational Experiments

Ryan Marshman

University College London

Given the ambitious nature of QGEM, which requires large masses to be placed in large superpositions for extended times, we have simultaneously taken two different tracks to explore how best to implement it. We have explored how to create as large a spatial splitting as possible using Stern-Gerlach interferometry and looked to determine how best to minimise the experimental parameters needed while still creating a witnessable signal of gravitationally mediated entanglement. In this talk, I will seek to provide an overview of our progress as we work towards the realisation of the QGEM protocol. I will also highlight the possibility of other uses for such a device, such as the detection of the gravitational metric and specifically its use as a gravitational wave detector.

Contrasting the fuzzball and wormhole paradigms for resolving the black hole information paradox

Samir Mathur

Ohio State University

The black hole information paradox arises from the emission of entangled pairs from the vacuum region around a horizon. In string theory one finds that microstates of black holes are horizon sized quantum objects called fuzzballs. These fuzzballs from their surface like normal bodies (i.e., not by pair creation from a vacuum), so there is no information paradox. We contrast this resolution of the paradox with the 'wormhole paradigm' where the horizon remains a local vacuum in some appropriate variables, but nonlocal effects (wormholes) can transport information from inside the hole to infinity.

Quantum test of Gravity by colliding Schrödinger's kittens

Anupam Mazumdar

University of Groningen

Quantum gravity has never been tested in a laboratory. I will provide criteria for testing the quantum fluctuation of a graviton in a laboratory by colliding non-relativistically two Schrödinger’s kittens and study how the final states would be entangled in this process. Realising such an experiment will be filled with challenges, and I will motivate the community why doing such an experiment is necessary for our understanding of both the foundations of quantum mechanics and gravity.

Progress towards the quantum measurement regime with optically levitated nanogram-scale masses

David Moore

Yale University

Levitating nanodiamond experiments towards a test of quantum gravity

Gavin Morley

Warwick University

We are building an experiment in which a nitrogen-vacancy-centre electron spin would be used to put a levitated nanodiamond into a spatial quantum superposition [1-3]. This would be able to test theories of spontaneous wavefunction collapse and is the first step of a much more ambitious experiment to test if gravitational effects can be in a quantum superposition [4, 5]. This talk will describe our current experimental design [6-11], and our latest experimental progress.

[1] A. T. M. A. Rahman, A. C. Frangeskou, M. S. Kim, S. Bose, G. W. Morley & P. F. Barker, Sci. Rep. 6, 21633 (2016).

[2] A. T. M. A. Rahman, A. C. Frangeskou, P. F. Barker & G. W. Morley, RSI 89, 023109 (2018).

[3] A. C. Frangeskou, A. T. M. A. Rahman, L. Gines, S. Mandal, O. A. Williams, P. F. Barker & G. W. Morley, NJP 20, 043016 (2018).

[4] S. Bose, A. Mazumdar, G. W. Morley, H. Ulbricht, M. Toroš, M. Paternostro, A. A. Geraci, P. F. Barker, M. S. Kim & G. Milburn, PRL 119, 240401 (2017).

[5] C. Marletto & V. Vedral, PRL 119, 240402 (2017).

[6] S. Bose & G. W. Morley, arXiv:1810.07045 (2018).

[7] M. Scala, M. S. Kim, G. W. Morley, P. F. Barker & S. Bose, PRL 111, 180403 (2013).

[8] C. Wan, M. Scala, G. W. Morley, A. T. M. A. Rahman, H. Ulbricht, J. Bateman, P. F. Barker, S. Bose & M. S. Kim, PRL 117, 143003 (2016).

[9] J. S. Pedernales, G. W. Morley & M. B. Plenio, PRL 125, 023602 (2020).

[10] R. J. Marshman, A. Mazumdar, G. W. Morley, P. F. Barker, S. Hoekstra & S. Bose, NJP 22, 083012 (2020).

[11] Z.-q. Yin, T. Li, X. Zhang & L. M. Duan, PRA 88, 033614 (2013).

Probing the interplay of quantum mechanics and gravity using a trapped atom interferometer

Cristian Panda

Berkley

Atom interferometers are quantum mechanical devices sensitive to gravitational and inertial forces, with applications in fundamental physics and inertial sensing in the field. Their performance is currently limited by the interrogation time available to freely falling atoms in Earth's gravitational field, as well as noise due to mechanical and acoustic vibrations. Our experiment probes gravitational potentials by holding, rather than dropping, atoms. We realize an interrogation time of 20 seconds by suspending the spatially separated atomic wave packets in an optical lattice. This record coherence is enabled by the smooth lattice wave fronts, which are mode-filtered by an optical cavity. This trapped geometry suppresses phase variance due to vibrations by three to four orders of magnitude, overcoming the dominant noise source in atom-interferometric gravimeters. The later part of the talk describes recent progress in characterizing and reducing dephasing of the interferometer. An upgraded optical lattice interferometer experiment is currently being commissioned, with the goal of increased sensitivity to gravity, opening the way for measurements probing the interface of quantum mechanics and gravity.

The Noise of Gravitons

Maulik Parikh

Arizona State University

For observational purposes, gravity is often regarded classically, obeying Newton's law or Einstein's equations. Here I will show that, when the spacetime metric is treated quantum-mechanically, the classical trajectories of falling objects are subject to random fluctuations ("noise"); intuitively, the fluctuations can be viewed as arising due to the bombardment of the falling objects by gravitons. Consequently, the classical geodesic deviation equation is replaced by a Langevin-like equation reminiscent of Brownian motion. This fundamental noise could be observable at gravitational wave detectors. The noise amplitude depends both on the detector sensitivity and on the quantum state of the gravitational field; it can be greatly enhanced for certain classes of quantum states. The spectrum of the noise is computable and appears to be correlated between distant detectors. Detection of this fundamental noise would provide experimental evidence for the quantization of gravity and the existence of gravitons.

Quantum optics at the interface with gravity

Igor Pikovski

Stockholm University

Experimental progress in controlling and manipulating quantum systems has opened new routes not only for novel applications, but also for fundamental research. In this talk, I will discuss some theoretical results on how quantum optical experiments can help probe the interplay between quantum physics and gravity. I will give an outline of tests of quantum gravity phenomenology in table-top experiments and general relativistic effects in the dynamics of matter-waves and photons.

Towards Robust Interferometry with Massive Particles

Martin Plenio

University of Ulm

In this talk I will consider some of the challenges that are involved when attempting to conduct interference experiments that are aimed at detecting quantum features of gravity. I will then proceed to discuss a new architecture that holds the potential for significant signal enhancements.

Decoherence effects in non-classicality tests of gravity

Simone Rijavec

University of Oxford

The experimental observation of a clear quantum signature of gravity is believed to be out of the grasp of current technology. However several recent promising proposals to test the possible existence of non-classical features of gravity seem to be accessible by the state-of-art table-top experiments. Among them, some aim at measuring the gravitationally induced entanglement between two masses which would be a distinct non-classical signature of gravity. We explicitly study, in two of these proposals, the effects of decoherence on the system's dynamics by monitoring the corresponding degree of entanglement. We identify the required experimental conditions necessary to perform successfully the experiments. In parallel, we account also for the possible effects of the Continuous Spontaneous Localization (CSL) model, which is the most known among the models of spontaneous wavefunction collapse. We find that any value of the parameters of the CSL model would completely hinder the generation of gravitationally induced entanglement.

What do the Gravitational Entanglement Lab Experiments Teach us about Quantum Spacetime

Carlo Rovelli

Aix-Marseille University

I analyse in detail the theoretical reason gravitational entanglement lab experiments are interesting for quantum gravity research. I explain why, at the light of what we know about nature, their completion would be good evidence that geometry is quantised. I present a general relativistic account of the experiment, where it is the proper time along a particle's worldline to be in quantum superposition. I consider the possible longer term future of the field, and the possibility of using these techniques to reveal also relativistic quantum gravity effects, as the discreteness of time.

Quantum information-driven tests of gravitationally-mediated entanglement

Jacob Taylor

NIST-Baltimore

We expect any quantum theory of gravity of be consistent at low energies and curvatures with the Newtonian limit of classical general relativity. I will explore what the semi-classical and quantum limits of the Newtonian interaction can look like, and discuss experimental approaches for bounding the capability of this interaction to create entanglement between two different, massive objects. Of particular interest will be seeing how the addition of assumptions regarding a quantum theory of gravity correspond to easier to implement tests of gravitationally-induced entanglement.

Relative Acceleration Noise Mitigation for Nanocrystal Matter-wave Interferometry: Application to Entangling Masses via Quantum Gravity

Marko Toros

University of Glasgow

Matter wave interferometers with large momentum transfers, irrespective of specific implementations, will face a universal dephasing due to relative accelerations between the interferometric mass and the associated apparatus. Here we propose a solution that works even without actively tracking the relative accelerations: putting both the interfering mass and its associated apparatus in a freely falling capsule, so that the strongest inertial noise components vanish due to the equivalence principle. In this setting, we investigate two of the most important remaining noise sources: (a) the non-inertial jitter of the experimental setup and (b) the gravity-gradient noise. We show that the former can be reduced below desired values by appropriate pressures and temperatures, while the latter can be fully mitigated in a controlled environment. We finally apply the analysis to a recent proposal for testing the quantum nature of gravity [S. Bose et. al. Phys. Rev. Lett 119, 240401 (2017)] through the entanglement of two masses undergoing interferometry. We show that the relevant entanglement witnessing is feasible with achievable levels of relative acceleration noise.

Probing gravity of quantum systems in the paradigm of levitated mechanics

Hendrik Ulbricht

University of Southampton

I will report on our recent progress with experiments with trapped nano- and micro-particles, especially with Meissner-levitated ferromagnets above a type-1 superconductor. We find a system with ultralow mechanical damping showing great potential for sensing tiny forces [1] and, apparently, independent from the standard quantum limit - which holds promise to detect record low magnetic fields and we discuss ideas for a ferromagnetic gyroscope [2], where the precession motional degree of freedom is used to sense tiny magnetic fields. We also discuss how other rotational degrees of freedom can be used for inertial and force detection. We apply force noise measurements to bound collapse models to test the quantum superposition principle in the macroscopic domain of large mass systems [3, 4]. We illustrate ideas to used levitated mechanical systems to probe into gravity interactions leading toward the experimental exploration of the interplay between quantum mechanics and gravity [5]. We also mention ideas to probe into the physics of quantum field theory effects in non-inertial reference frames based on spinning micro-particles [6, 7].

[1] Vinante, A., P. Falferi, G. Gasbarri, A. Setter, C. Timberlake, and H. Ulbricht, Ultrahigh mechanical quality factor with Meissner-levitated ferromagnetic microparticles, Phys. Rev. Appl. 13, 064027 (2020) with Editor's Suggestion, and arXiv:1912.12252.

[2] Fadeev, P., C. Timberlake, T. Wang, A. Vinante, Y. B. Band, D. Budker, A. O. Sushkov, H. Ulbricht, and D. F. J. Kimball Ferromagnetic Gyroscopes for Tests of Fundamental Physics, Quantum Sci. Technol. 6, 024006 (2021), and arXiv:2010.08731.

[3] Vinante, A., M. Carlesso, A. Bassi, A. Chiasera, S. Varas, P. Falferi, B. Margesin, R. Mezzena, and H. Ulbricht, Narrowing the parameter space of collapse models with ultracold layered force sensors, Phys. Rev. Lett. 125, 100404 (2020), and arXiv:2002.09782.

[4] Vinante, A., G. Gasbarri, C. Timberlake, M. Toroš, and H. Ulbricht, Testing Dissipative Collapse Models with a Levitated Micromagnet, Phys. Rev. Research 2, 043229 (2020) with Editor's suggestion, and arXiv:2008.06245.

[5] Carlesso, M., A. Bassi, M. Paternostro, and H. Ulbricht, Testing the gravitational field generated by a quantum superposition, New J. Phys. 21 093052 (2019), and arXiv:1906.04513.

[6] Braidotti, M. C., A. Vinante, G. Gasbarri, D. Faccio, and H. Ulbricht, Zel'dovich amplification in a superconducting circuit, Phys. Rev. Lett. 125, 140801 (2020), and arXiv:2005.03705.

[7] Lochan, K., H. Ulbricht, A. Vinante, S. K. Goyal, Detecting acceleration-enhanced vacuum fluctuations with atoms inside a cavity, Phys. Rev. Lett. 125, 241301 (2020), and arXiv:1909.09396.

Different degrees of reliability of lab-based tests of quantum aspects of gravity

Vlatko Vedral

Oxford University

I will present a range of possible tests of the quantum nature of gravity in the lab. They could, broadly speaking, be divided into those that involve superpostions of a single massive object and those that involve entanglement between two (or more) massive objects. I will explain why the later tests are much more convincing and will use information theoretic arguments to substantiate my claim.

Observational consequences of quantum gravity in interferometers

Kathryn Zurek

Caltech

I consider the uncertainty in the arm length of an interferometer due to metric fluctuations from the quantum nature of gravity, proposing a concrete microscopic model of energy fluctuations in holographic degrees of freedom on the surface bounding a causally connected region of spacetime. I make connection between the holographic model and a low energy effective theory, based on low-momentum degrees of freedom that I call “pixellons”.