*Redefining the foundations of physics in the quantum technology era*
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# BOOKLET OF ABSTRACTS

*Florian Marquardt - Max Planck Institute for the Science of Light, Germany*
Classical Neural Networks for Quantum Physics

Machine learning with artificial neural networks is revolutionizing science. The most advanced challenges require discovering answers autonomously. In the domain of reinforcement learning, control strategies are improved according to a reward function. The power of neural-network-based reinforcement learning has been highlighted by spectacular recent successes such as playing Go, but its benefits for physics are yet to be demonstrated. Here, we show how a network-based "agent" can discover complete quantum-error-correction strategies, protecting a collection of qubits against noise. These strategies require feedback adapted to measurement outcomes. Finding them from scratch without human guidance and tailored to different hardware resources is a formidable challenge due to the combinatorially large search space. To solve this challenge, we develop two ideas: two-stage learning with teacher and student networks and a reward quantifying the capability to recover the quantum information stored in a multiqubit system. Beyond its immediate impact on quantum computation, our work more generally demonstrates the promise of neural-network-based reinforcement learning in physics.

*Luca Mancino - Queen's University Belfast, UK*
Entropy Production in Continuously Measured Quantum Systems

The entropy production rate is a central object in non-equilibrium thermodynamics. Still, we lack definitions of this quantity that are easily manageable and general enough to encompass various experimentally interesting set-ups. In this talk, we characterise the excess entropy produced by a continuously monitored Gaussian system – a.k.a., the situation encountered in experiments like the ones of interest for TEQ – due to the observation process. We isolate the entropy production rate using the dynamics of the system in phase space. The end result is a generalised second-law which account for the information acquired by measuring the system.

*Tobias Donner – ETH Zurich, Switzerland*
Dissipation-induced instability in a quantum gas

Dissipative and unitary processes define the evolution of a many-body system. Their interplay gives rise to dynamical phase transitions and can lead to instabilities. We observe a non-stationary, rotating state in a synthetic many-body system with independently controllable unitary and dissipative couplings. Our experiment is based on a spinor Bose gas interacting with an optical resonator. The orthogonal quadratures of the resonator field coherently couple the Bose-Einstein condensate to two different atomic spatial modes whereas the dispersive effect of the resonator losses mediates a dissipative coupling between these modes. In a regime of dominant dissipative coupling we observe a chiral evolution and map it to a positional instability.

*Cyrille Solaro – Aarhus University, Denmark*
Photon recoil spectroscopy: Molecular ion spectroscopy and detection of motional heating of trapped charged particles

Thanks to their strong interaction with electric fields, ions are easily trapped, and once laser-cooled, their spatial extension can amount to a few tens of nanometers only. This allows for external perturbations from the environment to be controlled extremely well, leading to long coherence times required for high precision measurements. However, many atomic, most molecular ions and charged nanoparticles do lack nearly closed optical transitions, which are necessary for efficient translational cooling, but also for standard fluorescence state detection. This restriction can be overcome by sympathetically cooling the particle of interest with a single co-trapped laser-cooled atomic ion. This ion is often referred to as the "readout ion" since it can serve to detect single photon scattering events on the charged particle of interest through excitation of the two-particles systems common motion due to the photon momentum recoil. In addition, the readout ion can be used to detect any other motional heating mechanism the particle of interest is subjected to, like, e.g. heating induced by fluctuating trapping potentials as well as heating predicted by spontaneous collapse models. In this talk, I will present our recent achievements in implementing photon recoil spectroscopy (PRS) of a single Mg+ atomic ion co-trapped with a Ca+ ion. This experiment represents a crucial step towards PRS of rovibrational transitions in a single MgH+ as well as PRS of more complex molecular ions. Eventually, this universal detection scheme applied on very complex molecular ions might also be used for testing heating predicted by spontaneous collapse models.

*Andrew Steane – University of Oxford, UK*
Limits to quantum coherence from existing physics and the Paul trap as a probe of CSL

I first discuss two elements of known physics which present limits to the degree to which interference effects can be observed using interferometers. The first of these is the Unruh effect, the second is the gravitational wave (GW) background. The Unruh effect results in stochastic behaviour of the momentum of an object accelerated by non-gravitational forces, and consequently blurs the interference phase in an ordinary matter-wave interferometer. However, the calculation suggests this is too small an effect to rule out macroscopic interference. The GW background, on the other hand, is significant in that if it cannot be eliminated then it may limit macroscopic interference of ordinary bodies at distance scales of order millimetres. I then proceed to a discussion of the use of the Paul trap as a probe of continuous spontaneous localisation. Measurement of heating of the motion of a trapped microsphere can in principle reach a sensitivity of order nK per minute, in an apparatus protected from seismic noise and with challenging but feasible requirements on the background gas pressure. This makes the Paul trap one of the most promising experimental routes to place limits on, or detect, CSL.

*Luis Cortés Barbado - Institute for Quantum Optics and Quantum Information, Vienna*
Quantum Reference Frames: from particles to fields

In physics, the description of a system is done with respect to an idealized reference frame with classical properties (such as a lattice of rigid rods with synchronized clocks). This reference frame is usually not considered as a degree of freedom of the problem. However, in all practical situations the reference frame is indeed a physical system. If we believe that any physical system should ultimately be described by Quantum Mechanics, we would like to consider constructions in which reference frames are actually quantum systems. The notion of Quantum Reference Frames (QRF) has been extensively studied in the literature. In this talk, I will briefly introduce a recent work that provides a compelling construction of transformations between QRFs corresponding to non-relativistic quantum particles, finding that notions such as quantum superposition or entanglement can be (quantum) frame dependent. I will also introduce a possible extension of this QRFs construction to the description of quantum fields, and discuss its potential implications on an already well known phenomenon arising due to the frame-dependent description of quantum fields, namely the Unruh effect.

*Gabriel Hetet – ENS, France*
Spin-Mechanics with particles levitating in a Paul trap

T. Delord, P. Huillery, L. Nicolas, G.Hétet[1]
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[2]. 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[3] .

[1] Delord T. et al. Phys. Rev. Lett. 121 053602 (2018)
[2] Delord T., et al. arXiv:1905.11509 (2019)
[3] Huillery P. et al. ArXiv 1903.09699 (2019).

*Magdalena Zych – University of Queensland, Australia*
Relativity of quantum superpositions and its implications for collapse models

In modern physical theories only relative distance between a pair of systems has physical significance — and not their absolute position, which depends on the choice of a coordinate system. However, in quantum theory the scenario where a system A is localised while another system, B, is in a spatial superposition is considered to be physically different from the scenario where A is in a superposition, while B is localised. In particular, if A and B have very different masses, most ``collapse models'' make different predictions in the two scenarios. Here I will prove that if the superposed amplitudes of are related by a symmetry of dynamics, these two scenarios are fully equivalent in standard quantum theory. Most collapse models can thus be seen as violating translational symmetry rather than linearity of quantum mechanics. I will conclude with evidence that a collapse model satisfying translational symmetry is very strongly constrained by atom fountain interference experiments.

*Ward Stryve - K.M. Leuven, Belgium*
Cosmic acceleration as a quantum gravity effect

We consider a simplified model of quantum gravity using a mini-superspace description of an isotropic and homogeneous universe with dust. We derive the corresponding Friedmann equations for the scale factor, which now contain a dependence on the wave function. We identify wave functions for which the quantum effects lead to a period of accelerated expansion that is in agreement with the apparent evolution of our universe, without introducing a cosmological constant.

*Tracy Northup – University of Innsbruck, Austria*
Towards quantum optomechanics with nanospheres and trapped ions

It has been proposed to test the limits of quantum mechanics via matter-interferometry experiments in which the position of a levitated mesoscopic particle interferes with itself [1]. Such experiments will require (1) preparation of quantum states of the particle's motion, and (2) coherence times for those quantum states that are longer than the time required for interference via wave function expansion.
Concerning the first point, we are pursuing qubit-assisted state preparation [2]: we plan to couple both the center-of-mass motion of a nanoparticle and a dipole transition of a single calcium ion to an optical cavity, so that the ion can be exploited for nonlinear optomechanics. With regards to the second point, the use of a Paul trap to levitate the nanoparticle offers distinct advantages. In particular, it should be possible to work in an ultra-high vacuum (UHV) environment in the absence of the recoil heating effects that are a consequence of optical trapping. I will discuss the experimental system under development and describe UHV-compatible techniques we have recently demonstrated for loading and charging nanoparticles in a Paul trap [3]. Cooling of the particle's secular motion via electrical and optical feedback will be presented and contrasted with cooling in optical traps. Finally, I will outline the initial experiments that are planned under UHV conditions.
[1] F. Fröwis, P. Sekatski, W. Dür, N. Gisin, and N. Sangouard, Rev. Mod. Phys. 90, 025004 (2018)
[2] A. C. Pflanzer, O. Romero-Isart, and J. I. Cirac, Phys. Rev. A 88, 033804 (2013)
[3] D. S. Bykov, P. Mestres, L. Dania, L. Schmöger, T. E. Northup, arXiv:1905.04204 (2019)

*Stefan Nimmrichter - Max Planck Institute for the Science of Light, Germany*
Classical channel gravity in the Newtonian limit

We present a minimal model for the quantum evolution of matter under the influence of classical gravity in the Newtonian limit. Based on a continuous measurement feedback channel that acts simultaneously on all constituent masses of a givenquantum 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.

*Matteo Carlesso – University of Trieste/INFN, Italy*
The action of CSL noise: from single atoms to macroscopic systems

In this talk, I will review the Continuous Spontaneous Localization (CSL) model. I will give a particular focus on the action of CSL noise and which are its testable characteristic traits. Various experimental setups, differing in size, mass, and applied detection techniques, currently provide meaningful bounds on the CSL parameters. I will discuss two extensions to the CSL model, the dissipative and the non-white one, and which are the current experimental attempts in bounding their parameter space. Finally, I will present some of the proposals for future investigations.

*Tjerk Oosterkamp – University of Leiden, the Netherlands*
Approaching the quantum to classical transition from both sides: progress, difficulties and plans with mK mechanical resonators

We propose to experimentally address the question: When does a 'quantum measurement' take place? According to the Copenhagen interpretation, a wavefunction collapses when a measurement takes place. But even after 100 years we still do not understand under which circumstances a superposition of states should cease to exist, except that larger objects may be more likely candidates than microscopically small systems. We want to probe the quantum to classical boundary, with an experimental system that is closer to the boundary than any other. The main idea of the proposal is that on the quantum side, a mechanical force sensor behaves as a quantum object, while on the classical side it has turned into a force sensor that is a piece of classical measurement apparatus, and therefore causes a quantum state to collapse.

We have recently stumbled upon the fact that, using force sensing mechanical resonators, one can test models that mathematically describe the process of quantum collapse, because these models predict an ever so slight heating of the mechanical modes. We have carefully measured the temperature of the lowest mechanical modes of the force sensor, and find that it is only very slightly above the temperature of their environment. Our experiments have provided the tightest upper limits to the parameters in these models. We present the progress of improving the bounds and our future plans to improve upon our experiment, with the possibility in mind to actually determine the parameters that describe these models, rather than providing an upper limit. With such experiments we hope to pin down the quantum to classical boundary.

Secondly, we propose an even more accurate experiment to determine the wavefunction collapse parameters. By reducing the coupling of our force sensors with the environment and the operating temperature of our experiment further, we reach the parameter regime where we can demonstrate that our force sensing mechanical resonators can be brought in a superposition of states. This can be done by entangling it with an electron spin that is in superposition. However, to achieve this, the ordinary dephasing due to the coupling to microscopic degrees of freedom in the environment must be made sufficiently low. We present a calculation of the expected visibility of the interference that arises when our massive force sensor is brought in superposition and discuss what is needed to achieve the necessary experimental parameters and how we are working to achieving this.

We are excited about both versions of the experiment because we will either provide the most massive mechanical interference experiment to date or we will find where the boundary between classical and quantum physics lies. Perhaps, in the future, these experiments will lead us to a clue about what it is that causes wave function collapse to arise.

*Antonio Pontin – UCL, London*
<u>An ultra-narrow linewidth levitated nano-oscillator for testing dissipative wavefunction collapse</u>

Levitated nano-oscillators are considered as a promising platform to test quantum mechanics and fundamental physics in an unprecedented high mass range. The extreme isolation that can be achieved in such systems allow to reduce the decoherence processes that are crucial for these experiments. In recent years, there has been significant progress in the field with the quantum regime near at hand. Even in the classical regime, however, it is possible to perform meaningful experiments to test collapse models. These are modifications to standard quantum mechanics that introduce a transition to classicality for macroscopic objects, leaving an unmodified quantum dynamic at microscopic scales, and offer a potential solution to the measurement problem.
In my talk, I will describe our progress toward testing collapse models with a highly charged nanoparticles levitated in a Paul trap. We recently investigated possible detection schemes to measure the motion of a low frequency oscillator held in an ultra-cryogenic environment and compared standard optical detection to a SQUID based scheme. Finally, the characterization of our latest trap allowed us to precisely measure the gas damping down to very low pressures. We exploited this measurement to place new bounds to the dissipative variant of two important collapse models, namely, the Continuous spontaneous localization and the Diósi-Penrose.

*Stefan Gerlich - University of Vienna, Austria*
<u>Long-Baseline Universal Matter-wave interferometry</u>

In recent years there has been a growing experimental effort to create and investigate highly macroscopic quantum states. Matter-wave interferometers of the Talbot-Lau type have proven to be particularly suited for the exploration of the quantum nature of massive particles.
We here report on the completion a near-field matter-wave interferometer of the newest generation. At a baseline of two meters, the new Viennese *Long-baseline Universal Matter-wave Interferometer* (LUMI) outperforms its predecessor by one order of magnitude with regard to the accessible mass regime and by a factor 100 in force sensitivity. LUMI will be able to operate with de Broglie wavelengths of less than 50 fm. This will make it possible to study the quantum superposition of particles in the range of 100,000 amu and to thus set stricter bounds for potential modifications of quantum theory such as objective collapse models.
LUMI is sensitive to external forces as small as $10^{-26}$N. This puts high experimental demands on the vibration insulation and even necessitates compensation of the Coriolis force but also makes LUMI and ideal platform for precision metrology experiments. LUMI offers the option to switch between different diffraction mechanisms and is thus suited for complex organic molecules and metal clusters as well as for single atoms. The modular design of the interferometer also allows for the introduction of electric and magnetic fields, collision cells and spectroscopy lasers. This makes it possible to explore the electronic, optical and magnetic and through these also the structural properties of a large and diverse class of particles with high precision in free flight.
I will present the very first experimental results of our new device and provide an overview of its future prospects.

*Edward Laird*
<u>DIsplacemon electromechanics: an approach towards testing quantum interference in a tethered nanomechanical resonator</u>

We introduce the `displacemon' electromechanical architecture that comprises a vibrating nanobeam, e.g. a carbon nanotube, flux coupled to a superconducting qubit. This platform can achieve strong and even ultrastrong coupling enabling a variety of quantum protocols. We use this system to describe a protocol for generating and measuring quantum interference between two trajectories of a nanomechanical resonator. The scheme uses a sequence of qubit manipulations and measurements to cool the resonator, apply an effective diffraction grating, and measure the resulting interference pattern. We simulate the protocol for a realistic system consisting of a vibrating carbon nanotube acting as a junction in a superconducting qubit, and we demonstrate the feasibility of generating a spatially distinct quantum superposition state of motion containing more than $10^6$ nucleons.

*Jason Ralph – University of Liverpool, UK*
Statistical Methods for Distinguishing Quantum and Classical Dynamics

We discuss statistical methods to distinguish dynamical models using experimentally recorded time-trace data. We examine methods that can be used to distinguish between quantum and classical dynamical models, and provide the conditions that optimize quantum hypothesis testing using a simplified theoretical model and an experimentally realisable system.

*Kristian Piscicchia – INFN Frascati, Italy*
Quantum Mechanics Studies in the Cosmic Silence

The VIP-2 at the Underground Gran Sasso Laboratory (LNGS) experiment aims to perform high precision tests of the Pauli Exclusion Principle for electrons. The spin-statistics connection can be only demonstrated within Quantum Field Theory, hence experimental evidence of even a tiny violation of the PEP would be an indication of physics beyond the Standard Model. The method consists in circulating a DC current in a copper strip, searching for the X radiation emission due to a prohibited transition (from the 2p level to the 1s level of copper when this is already occupied by two electrons). VIP already set the best limit on the PEP violation probability for electrons $\beta^2/2 < 4.7 \cdot 10^{-29}$, the goal of the upgraded VIP-2 experiment is to improve this result of two orders of magnitude at least. The experimental apparatus and the results of the analysis of a first set of collected data will be presented. The extremely low background environment of LNGS is also suitable for investigating one of the main mysteries of Quantum Mechanics Foundations: the measurement problem. Dynamical reduction models of the wave function collapse are at test at LNGS, with an experimental setup based on High Purity Ge Detectors and an utmost radio-pure Roman lead target. Preliminary results will be shown.

*Ron Folman - Ben-Gurion University of the Negev, Israel*
New opportunities with the atom chip

The atom chip has been maturing for 20 years now. It enables a high level of control over magnetic, electric and light fields, in magnitude, time and space. To illustrate its capabilities, I will describe several recent experiments. I will then conclude with some examples of how the atom chip may be used for fundamental physics searches.

*Alessio Belenchia - Queen's University Belfast, UK*
*Near Field Interferometry with Large Particles*

Recent progress in matter-wave interferometry aims to directly probe the quantum properties of matter on ever-increasing scales. However, in order to perform interferometric experiments with massive mesoscopic objects, taking into account the constraints on the experimental set-ups, the point-like particle approximation needs to be cast aside. In this talk, we consider near-field interferometry based on the Talbot effects with a single optical grating for large spherical particles beyond the point-particle approximation. We account for the suppression of the coherent grating effect and, at the same time, the enhancement of the decoherence effects due to scattering and absorption of grating photons.

*Sougato Bose – University College London*
*Superpositions of Mesoscopic Objects for Sensing Quantum Gravity and Gravitational Waves*

We will show two fundamental applications of quantum superpositions of spatially separated states of mesoscopic objects (nano- and micro-spheres). Firstly, we are going to show how convenient it may be to prepare and probe such superpositions through a pure ancillary system such as a spin. Next, we are going to show how an entanglement between two such interferometers can be generated purely through the Newtonian interaction between the masses and that this can be probed, at the end of the interferometry, purely by measuring the correlations between spins. We are going to justify why, under the assumption of locality of physical interactions and under a reasonable definition of classicality, the above entanglement signifies the qualitatively quantum nature of gravity. We are also going to discuss how the same spin-induced and probed superpositions will open up the ability to detect low frequency gravitational waves, immune to initial thermal noise, with a meter-scale apparatus.

*Andrea Vinante – University of Southampton, UK*
Progress in testing spontaneous localization models with low temperature micromechanical resonators

I will report on recent advances in testing spontaneous localization models, in particular the standard CSL model, by monitoring micromechanical resonators at very low temperature. The first experiment I will discuss is based on a well-established cantilever-based technique, in which we have optimized the mass load to enhance the effect of CSL at the standard length rc=100 nm. The test mass is fabricated as a multilayer structure to exploit the dependence of the CSL-induced force noise on mass density variations. Experimental data are significantly constraining the Adler parameter range. In the second part, I will introduce a new class of mechanical systems based on ferromagnetic microspheres levitated in a superconducting trap and monitored by a SQUID. This approach appears promising, as it allows stable cryogenic-compatible and fully passive levitation without need for any external active element. First experiments have demonstrated mechanical quality factor in excess of 10 million, paving the way towards more stringent tests of collapse models.