

*Redefining the foundations of physics in the quantum technology era  
Trieste, 16-19 September 2019*

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.

***Tobias Donner – ETH Zurich, Switzerland***

Dissipation-induced instability in a quantum gas

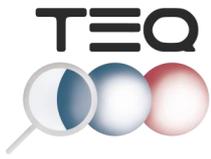
Dissipative and unitary processes define the evolution of a many-body system. Their interplay gives rise to dynamical phase transitions and can lead to instabilities. We observe a non-stationary, rotating state in a synthetic many-body system with independently controllable unitary and dissipative couplings. 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.

***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

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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.

*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*

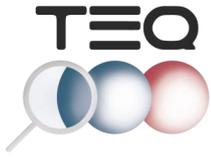
Quantum Mechanics Studies in the Cosmic Silence

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.

*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 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.



**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 <sup>[1]</sup>. 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 <sup>[2]</sup>: 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 <sup>[3]</sup>. 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)

**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.

**Gabriel Hetet – ENS, France**

Spin-Mechanics with particles levitating in a Paul trap

T. Delord, P. Huillery, L. Nicolas, G.Hétet<sup>1</sup>

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<sup>[2]</sup>. 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<sup>[3]</sup>.

[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).

***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.

***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.

***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.

***Stefan Gerlich - University of Vienna, Austria***

Long-Baseline Universal Matter-wave interferometry

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 an 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.

***Antonio Pontin – UCL, London***

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

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.

***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.

***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.

***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.