Fundamental Problems in Quantum Physics

September 10-12, 2024

Abstracts booklet

LECTURES

Angelo Bassi (University of Trieste, Italy)

Title: Are there quantum jumps?

Quantum mechanics is fundamentally based on the superposition principle, which accounts for both its remarkable successes and its conceptual challenges. The failure of superpositions to extend from the microscopic to the macroscopic scale remains a contentious issue. To address this, models of spontaneous wave function collapse have been proposed. These models modify Schrödinger's dynamics to reflect a gradual failure of quantum superpositions in larger systems, making them subject to empirical testing. However, the deviations predicted by these models are minute and demand highly precise measurements. I will examine these collapse models and discuss the latest experimental tests that have been conducted.

Fabio Benatti (University of Trieste, Italy)

Title: Non Markovian dynamics and information flows

Lecture I

The first lecture will focus upon quantum dynamics with explicitly time-dependent generator and the properties of positive and completely positive divisibility in connection with information flowing out and into an open quantum system.

Lecture II

Starting from the physics of complete positivity, the second lecture will discuss the phenomenon of super-activation of back-flow of information that might set in by the statistical coupling of an open quantum system with a copy of itself.

Hendrik Ulbricht (University of Southampton, UK)

Title: Testing quantum mechanics with levitated mechanical systems

I will discuss some of the recently popular proposals for testing quantum mechanics and gravity by experiments with massive quantum systems in the laboratory. I will showcase some of the models describing wavefunction collapse and the role which gravity as well as noise might have in this. I will work out what features experiments must possess to allow for testing physics according to these models and finally review the state of play for actual experimental tests.

TALKS

Davide Giordano Ario Altamura (University of Trieste, Italy)
Title: Non-interferometric rotational test of the Continuous Spontaneous Localisation model
The Continuous Spontaneous Localisation (CSL) model is the most studied among the collapse models, which describes the breakdown of the superposition principle for macroscopic systems. This model can be tested by a wide range of experiments, in particular, the non-interferometric tests aim at detecting the Brownian-like motion induced by the CSL model. Monitoring the rotational degrees of freedom of a macroscopic optomechanical system seems to represents a promising way to test this model.

Oliviero Angeli (University of Trieste, Italy)
Title: A fundamental ambiguity in Open Quantum Systems
It is well known that Lagrangians which differ by a total derivative encode the same physics. This is true classically and holds also quantum mechanically. We show, however, that in the context of open quantum systems, two Lagrangians that differ by a total derivative -or two unitary equivalent hamiltonians- can lead to very different predictions. We identify the root of this issue in the non commutativity of tracing over an environment and performing a global unitary. Faced with this fundamental inequivalence of descriptions, we put forth a criterion that allows one to choose between such Lagrangians. We'll analyse the reduced dynamics of QED as a case study to highlight the main discrepancies of the desciptions and to discuss in a concrete setting our proposed criterion.

Marion Cromb (University of Southampton, UK)
Title: Quantum Physics in Rotating Frames
The way quantum phenomena are affected by the frame of reference in which they occur is deeply connected to one of the most fundamental mysteries - the unification of quantum mechanics and general relativity. Some of the theorised effects are very well known, others less so, and direct experimental tests have been relatively overlooked. I can present my experimental work in two different areas. The first, how photon entanglement can be altered in rotating frames. The second, how certain (classical) field modes can be amplified by rotating absorbers, and prospects for seeing the effect on a quantum level.

Michael Drewsen (Aarhus University, Denmark)
Title: Search for bosons beyond the Standard Model through precise isotope shift measurements of the electronic structure in atomic ions
By combining high-resolution spectroscopy of the 3d 2D3/2 − 3d 2D5/2 interval with an accuracy of ~20 Hz using direct frequency-comb Raman spectroscopy with isotope shift measurements of the 4s 2S1/2 ↔ 3d 2D5/2 transition in all stable even isotopes of Ca(A)+ (A = 40, 42, 44, 46, and 48), we have in the recent past been able to carry out a King plot analysis with at the time unprecedented sensitivity to coupling between electrons and neutrons by bosons beyond the Standard Model. We will discuss our results in the context of newer improved results and point to how one might eventually improve on the bounds currently set by other methods in the mass range of 10 to 10^8 eV/c^2.

Laria Figurato (University of Trieste, Italy)
Title: On the effectiveness of the collapse in the Diósi-Penrose model
The possibility that gravity plays a role in the collapse of the quantum wave function has been considered in the literature, and it is of relevance not only because it would provide a solution to the measurement problem in quantum theory, but also because it would give a new and unexpected twist to the search for a unified theory of quantum and gravitational phenomena, possibly overcoming the current impasse. The Diósi-Penrose model is the most popular incarnation of this idea. It predicts a progressive breakdown of quantum superpositions when the mass of the system increases; as such, it is susceptible to experimental verification. Current experiments set a lower bound R_0 ≳ 4Å for the free parameter of the model, excluding some versions of it. In this work we search for an upper bound, coming from the request that the collapse is effective enough to guarantee classicality at the macroscopic scale: we find out that not all macroscopic systems collapse effectively. If one relaxes this request, a reasonable (although to some degree arbitrary) bound is found to be: R_0 ≲ 10^6 Å. This will serve to better direct future experiments to further test the model.

José Luis Gaona Reyes (University of Trieste, Italy)
Title: Can we incorporate spontaneous collapse in the Wheeler-DeWitt equation?
In this talk, I will review the basic concepts of the canonical quantization of General Relativity, focusing on the emergence of the Wheeler-DeWitt equation. By working with a concrete toy model which considers gravity and a perfect fluid, I will describe how to incorporate a spontaneous collapse mechanism in the corresponding Wheeler-DeWitt equation. This mechanism is inspired in the properties of dynamical collapse models. I will also discuss the physical implications of the incorporation of this mechanism.

Trinidad Lantaño (Universität Ulm, Germany)
Title: Entanglement of Rotational States as Evidence for Quantum Gravity
We present a novel approach to investigating the quantum nature of gravity by probing its capacity to generate entanglement. Unlike existing methods that focus on correlations between the quantized center-of-mass degrees of freedom of two systems under a Newtonian potential, our study explores a tree-level relativistic correction that entangles the angular momentum degrees of freedom. This approach does not require the preparation of states delocalized in position space, but rather in angular momentum space. Importantly, the determining factor is not the mass of the probes, but their angular momentum. We demonstrate that the optimal entanglement rate is achieved with states maximally delocalized in angular momentum, yet significant quantum correlations can still emerge between two rotating systems each initialized in a non-superposed state. Additionally, we analyze the robustness of the generated entanglement against common sources of noise

Emanuele Panella (University College London, UK)
Title: Hybrid classical-quantum gravity and cosmological implications
After a summary of recent results on the unique class of theories that consistently couple classical and quantum degrees of freedom, we discuss the application of the framework to cosmological settings in which quantum matter back-reacts on classical geometry. As a toy model, we study a stochastic Einstein-de Sitter Universe, discussing how LambdaCDM phenomenology can arise due to the stochastic fluctuations that are inevitable in a consistent classical-quantum theory of gravity.

Nicolò Piccione (University of Trieste, Italy)
Title: Extending the CSL Model by means of Generalized Mass Dependence
The Continuous Spontaneous Localization (CSL) model, a widely studied spontaneous collapse model, has been extended in various ways, including non-Markovian and dissipative modifications. However, the model's strength dependence on the square of the mass has rarely been debated. Recently, it has been suggested that a strength proportional to the mass might be more natural and could simplify connections with gravitation. In this paper, we generalize the CSL model to allow its mass dependence to be a generic function of the mass. We demonstrate that many key properties of the CSL model remain valid under this generalization. By focusing on cases where the mass dependence is a power of the mass, we derive approximate formulas for the dynamics of rigid bodies and the radiation emission induced by spontaneous collapses. Finally, we explore how the existing lower and upper bounds for the standard CSL model translate to this generalized version, finding that a higher mass dependence is unlikely, while a lower one significantly broadens the range of allowed parameters.

Kyrylo Simonov (University of Vienna, Austria)
Title: Quantum theory with indefinite causal order and time direction
Although quantum circuits are the most popular model of modern quantum computing, it is not the ultimate computational paradigm compatible with quantum mechanics. Indeed, in the last decade, a lot of effort has been put to develop more general higher-order models of quantum computing, which go beyond transformations of input quantum states. The paramount example is given by quantum combs, supermaps that can be considered as transformations of quantum gates on a quantum circuit board and tracked back to Church's lambda-calculus allowing to compute functions of functions. Nevertheless, quantum combs as transformations of quantum operations represent just a particular case of supermaps allowed by quantum mechanics. Discovery of quantum SWITCH, a supermap that puts quantum operations into a coherent superposition of their causal orders and cannot be deterministically reduced to a quantum circuit, has suggested a higher-order computation model without definite causal order of quantum operations based on transformations of quantum combs. On the other hand, while fundamental laws of physics do not depend on the direction of time, our everyday experience suggests an opposite observation, namely, time flows in the forward direction, from past to future. As it can be attributed to the way how an agent interacts with physical system, the possibility of interaction in backward direction, i.e., from future to past, has been questioned. Such intuition can be already found in quantum mechanics formulated in the terms of two-time states that treats pre-selected and post-selected ensembles equally. This has lead to a new class of supermaps, which relax the well-defined direction of time in a quantum operation, i.e., input-output direction. Such supermaps cannot be deterministically reduced to a quantum circuit, which implied a well-defined direction of propagation of a qubit. In this talk, we introduce a theoretical framework for description of supermaps of this kind and discuss its applications.

Michael Suleymanov (Bar-Ilan University, Israel)
Title: Uncertainties and covariances in the framework of spatiotemporal quantum reference frames
The perspective-dependence of position and momentum uncertainties, as well as their correlations, is studied in the framework of nonrelativistic spatiotemporal quantum frames of reference [M. Suleymanov, I.L. Paiva, E. Cohen, Nonrelativistic spatiotemporal quantum reference frames, Phys. Rev. A 109, 032205 (2024)]. One of the results [M. Suleymanov, A. Carmi, E. Cohen, Uncertainties

and covariances in the framework of spatiotemporal quantum reference frames, forthcoming] is that, even in the non-interacting case, the Heisenberg uncertainty relations of a certain particle described by different observers do not coincide in general. What is invariant and constant for all observers, in the current framework, is the determinant of the frame-dependent total covariance matrix [A. Carmi, E. Cohen, Relativistic independence bounds nonlocality, Sci. Adv. 5, eaav8370 (2019)]. A generalized version of uncertainty relations is obtained for the relational description that is affected by the correlations between all observables in a chosen frame.

Chris Timberlake (University of Southampton, UK)
Title: Magnetic levitation: A platform for testing fundamental physics
Levitated mechanical oscillators have emerged as promising candidates for generating macroscopic quantum states and for precise sensing. Magnetic levitation has the added advantage of having a passive trapping mechanism, resulting in low decoherence rates due to being well decoupled from the environment. Here I will present experimental work on superconducting levitation of magnets and discuss progress on feedback cooling of translational and librational mechanical modes, as well as experiments to use levitated magnets to measure small gravitational accelerations. I will then discuss the possibility of utilising cooling and squeezing protocols to generate non-Gaussian states of motion, before demonstrating how magnets can be used as for non-interferometric tests of spontaneous collapse models.

Marko Toroš (University of Glasgow, UK)
Title: Generating quantum non-local entanglement with mechanical rotations
Recent experiments have searched for evidence of the impact of non-inertial motion on the entanglement of particles. The success of these endeavours has been hindered by the fact that such tests were performed within spatial scales that were only "local" when compared to the spatial scales over which the non-inertial motion was taking place. We propose a Sagnac-like interferometer that, by challenging such bottlenecks, is able to achieve entangled states through a mechanism induced by the mechanical rotation of a photonic interferometer. The resulting states violate the Bell-Clauser-Horne-Shimony-Holt (CHSH) inequality all the way up to the Tsirelson bound, thus signaling strong quantum nonlocality. Our results demonstrate that mechanical rotation can be thought of as resource for controlling quantum non-locality with implications also for recent proposals for experiments that can probe the quantum nature of curved spacetimes and non-inertial motion.
Toroš, Marko, Maria Chiara Braidotti, Mauro Paternostro, Miles Padgett, and Daniele Faccio. "Generating quantum non-local entanglement with mechanical rotations." arXiv preprint arXiv:2407.14276 (2024).

Bassano Vacchini (University of Milan, Italy)
Title: Jumps, collapses and reduced dynamics
It is partially known that dynamical reduction models arise building on the quantum mechanics formalism that provides a description of the time evolution of a quantum system in the presence of measurements by other quantum degrees of freedom, where neglecting measurement outcomes one obtains a reduced dynamics. This formalism was initiated in the study of the foundations of quantum mechanics and has been thoroughly developed and extensively used in the theory of open quantum systems. We will consider a few examples to elucidate these facts. We will point out that the celebrated GRW master equation is invariant under translations, reflecting the homogeneity of space,

and arises as a particular realization of a general class of translation-covariant Markovian master equations. Such master equations are typically used for the description of decoherence due to momentum transfers between the system and the environment. We will further consider the effect of unbounded energy-increase in certain dynamical reduction models from the perspective of a realistic system-environment interaction. References: B. Vacchini, Open Quantum Systems: Foundations and Theory (Springer, 2024); A. Smirne and A. Bassi, Dissipative Continuous Spontaneous Localization (CSL) model, Sci. Rep. vol. 5, 12518 (2015); B. Vacchini, On the precise connection between the GRW master-equation and master-equations for the description of decoherence, J. Phys. A: Math. Theor. vol. 40, pp. 2463-2473 (2007); A. Bassi, E. Ippoliti and B. Vacchini, On the energy increase in space-collapse models, J. Phys. A: Math. Gen. vol. 38, pp. 8017-8038 (2005).

Qiongyuan Wu (Queen's University Belfast, UK)
Title: Squeezing below the ground state of motion of a continuously monitored levitating nanoparticle
Squeezing is a crucial resource for quantum information processing and quantum sensing. In levitated nanomechanics, squeezed states of motion can be generated via temporal control of the trapping frequency of a massive particle. However, the amount of achievable squeezing typically suffers from detrimental environmental effects. We propose a scheme for the generation of significant levels of mechanical squeezing in the motional state of a levitated nanoparticle by leveraging on the careful temporal control of the trapping potential. We analyze the performance of such a scheme by fully accounting for the most relevant sources of noise, including measurement backaction. The feasibility of our proposal, which is close to experimental state-of-the-art, makes it a valuable tool for quantum state engineering.

Giorgio Zicari (Queen's University Belfast, UK)
Title: Critical quantum metrology for fundamental physics
Quantum metrology provides a useful toolkit for parameter estimation problems ranging from fundamental physics to applications in the field of quantum technology. We discuss non-equilibrium probing schemes that allow to dynamically encode information about the parameter to be estimated in a parameter regime where a many-body system is close to a critical point. It is indeed known that quantum criticality greatly enhances the ability to discriminate the Hamiltonian parameters of a given system. We discuss the extension of this result to dissipative dynamics of a quantum Ising chain described by a Lindbladian master equation. In particular, we investigate the optimal strategy to estimate the collapse rate entering in the dissipative master equation of the Continuous Spontaneous Localization (CSL) model.