Fundamental Problems in Quantum Physics

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Abstracts booklet

LECTURES

Alberto Imparato (University of Trieste, Italy)

Title: Fluctuation theorem in open quantum systems

I will discuss a general quantum fluctuation theorem for the entropy production of an open quantum system coupled to multiple environments, not necessarily at equilibrium.

When the interaction between the system and the bath(s) is explicitly taken into account the fluctuation theorem amounts to a relation between time-reversed dynamics of the global density matrix and a two-time correlation function along the forward dynamics involving the baths' entropy alone. As such, the theorem reflects the asymmetry between the forward and the time-reversed evolution of the system.

When restricted to the weak-coupling and Markovian regime, the theorem holds for both local and global master equations, corroborating the thermodynamic consistency of local quantum master equations.

Francesco Scazza (University of Trieste and CNR-INO, Italy)

Title: Cold atoms for precision measurements and many-body physics

Experiments with neutral atoms trapped at sub-μK temperatures have emerged as a powerful platform for high-precision tests of fundamental physics and for the controlled exploration of complex many-body quantum phenomena. In this lecture, I will introduce the essential techniques and tools that enable these advances and discuss some of the most recent developments.

Roderich Tumulka (University of Tuebingen, Germany)

Title: Bohmian mechanics, its meaning and its consequences

I will discuss some aspects of Bohmian mechanics, including its relation to no-hidden-variables theorems, how it solves the measurement problem, its extension to relativistic space-time, its relation to collapse theories, and the arrival-time question. As John Bell wrote, Bohmian mechanics ``exercises the mind in a very salutary way"; having a good grasp of how this theory works is beneficial for any research work in the foundations of quantum mechanics.

TALKS

Davide Giordano Ario Altamura (University of Trieste, Italy)
Title: Probing Quantum Collapse with Rotational Dynamics
Spontaneous wavefunction collapse models, such as the Continuous Spontaneous Localization (CSL) model, provide a promising approach to address the quantum measurement problem by introducing stochastic, nonlinear modifications to the Schrödinger equation. We present new experimental constraints on the CSL model derived from recent high-precision measurements of optomechanical systems rotational motion. Using data from both the LISA Pathfinder mission and a state-of-the-art table-top short-distance gravity experiment, we show that rotational noise can place competitive, and in some regimes stronger, bounds on CSL parameters compared to translational tests. Our analysis highlights the conditions under which rotational degrees of freedom offer enhanced sensitivity to collapse-induced noise. Additionally, we design an optimized geometry of the test mass to amplify the CSL effect and access previously unexplored regions of the parameter space. These findings underscore the potential of rotational tests as a powerful tool for future dedicated experimental investigations of collapse models.

Oliviero Angeli (University of Trieste, Italy)
Title: Entanglement in Hybrid Classical-Quantum Theories of Gravity
Markovian master equations underlie many areas of modern physics and, despite their apparent simplicity, they encode a rich and complex dynamics which is still under active research. We identify a class of continuous variable Markovian master equations for which positivity and complete positivity become equivalent. We apply this result to characterize the positivity of the partially transposed evolution of bipartite Gaussian systems, which encodes the dynamics of entanglement. Finally, the entangling properties of models of classical gravity interacting with quantum matter (i.e. hybrid models of gravity) are investigated in the context of the experimental proposals to detect gravitationally induced entanglement. We prove that entanglement generation can indeed take place within these models. In particular, by focusing on the Di´osi-Penrose model for two gravitationally interacting masses, we show that entanglement-based experiments have the potential to either falsify the model entirely or constrain the free parameter of the model R_0 up to values six orders of magnitude above the current state of the art.

Simone Artini (University of Palermo, Italy)
Title: Non-equilibrium thermodynamics of gravitational objective-collapse models
We investigate the entropy production in the Diosi-Penrose (DP) model, one of the most extensively studied gravity-related collapse mechanisms, and one of its dissipative extensions. To this end, we analyze the behavior of a single harmonic oscillator, subjected to such collapse mechanisms, focusing on its phase-space dynamics and the time evolution of the entropy production rate — a central quantity in non-equilibrium thermodynamics. Our findings reveal that the original DP model induces unbounded heating, producing dynamics consistent with the Second Law of thermodynamics only under the assumption of an infinite-temperature noise field. In contrast, its dissipative extension achieves physically consistent thermalization in the regime of low dissipation strength. We further our study to address the complete dynamics of the dissipative extension, thus including explicitly non-Gaussian features in the state of the system that lack from the low-dissipation regime, using a short-time approach.

Nicolas Boulle (Mid Sweden University, Sweden)
Title: Subsystems' (in)dependence in gravitationally induced entanglement proposals

Gravitationally induced entanglement (GIE) proposals suggest that if two spatially separated masses interacting only through gravity become entangled, gravity must be a quantum entity. However, these proposals are framed within quantum information theory rather than quantum field theory (QFT), leading to hidden assumptions about the notion of subsystems and entanglement.
At the QFT level, a massive particle is described by a scalar field, which can be "dressed" to make it gauge invariant. Typically, the observable algebras of two such spacelike-separated dressed fields commute, indicating their independence. However, in the presence of gravity, this is not necessarily the case: gravitational dressing can induce non-commutative algebras, challenging the assumption that the two systems are truly independent subsystems. If the masses are not independent, their states may not naturally belong to separated Hilbert spaces, and there may be a need for a modification in the quantum information description of GIE proposals.
In this talk, we explore the implications of gravitational dressing on subsystem independence and its consequences for GIE experiments. We argue that a proper understanding of entanglement in a GIE context requires revisiting assumptions, potentially impacting the conclusions drawn from the experiments.

Lajos Diosi (Wigner Research Centre for Physics Budapest, Hungary), TBC
Title: Relativistic Covariant Formalism of Quantum Measurement and Wavefunction Collapse
TBA

Giorgos Eftaxias (Korea Institute for Advanced Study (KIAS), Korea)
Title: Advantages of multicopy nonlocality distillation and its application to minimizing communication complexity
Nonlocality has been proved a resource for various information-processing tasks, a fact that naturally raised its distillation endeavours. Here we introduce several nonlocality distillation schemes, some are sequential algorithms that repeatedly discover optimal two-copy protocols, while others are genuine three-copy protocols. The impact of our schemes is twofold. On the one hand, they unlock the distillability of quantum correlations not known to be distillable before, this way, they offer practical distillation of observed correlations by easy means. On the other hand, they uncover more non-signalling correlations that trivialize communication-complexity, and others that defy information-causality. This brings us closer to an understanding of the sets of nonlocal correlations that can be recovered from information-theoretic postulates, which in turn, enhances our understanding of what is special about quantum theory.
[1] Eftaxias, G., Weilenmann, M. and Colbeck, R., 2023. Advantages of multicopy nonlocality distillation and its application to minimizing communication complexity. Physical Review Letters, 130(10), p.100201.
[2] Eftaxias, G., Weilenmann, M. and Colbeck, R., 2023. Multisystem measurements in generalized probabilistic theories and their role in information processing. Physical Review A, 108(6), p.062212.

David Ellerman
Title: Objective Indefiniteness: The interpretation implicit in the mathematics of quantum mechanics
QM cannot be interpreted using our classical-physics intuitions of a fully definite reality, i.e., definiteness “all the way down” (or full haecceity) as exemplified in Leibniz’s Principle of Identity of Indistinguishables. The Heisenberg Indeterminacy Principle shows that conjugate observables cannot both have definite (eigen) values. Our conception of quantum reality must include objective indefiniteness.

Recent developments in mathematics indicate that modelling objective indefiniteness gives some insight into QM. (Ellerman 2024a; 2024b). The logic for the classical notion of full definiteness is the usual Boolean logic of subsets; an element is definitely in a subset or in its complement. But there is a category-theoretically dual logic of partitions (or equivalence relations) that is the logic to model indistinctions, indefiniteness, and indistinguishability (from quiddity without haecceity to full haecceity). The duality between subsets and partitions (or quotient sets) is highly developed in the reverse-the-arrows duality of category theory that provides the warp and woof (subobjects and quotient objects) of mathematics and extends to a fundamental duality in the exact sciences (Ellerman 2024c)

As Boole recognized, the quantitative version of subset logic provided the foundation for probability theory; the quantitative version of the dual partition logic provides a new logical foundation for information theory (classical and quantum logical entropy, Ellerman 2021; 2022).

The bridge from the mathematics of partitions to QM math is obtained by a semi-algorithmic procedure (known in the mathematics folklore), the 'yoga' of linearization. That makes it clear that the basic quantum notions of state, observable, and state reduction ("measurement") among other QM notions are the Hilbert-space versions of the underlying set math notions of partition logic and logical entropy. Running the yoga in reverse allows the construction of a simple toy or pedagogical model of key QM notions in terms of sets modeled as vectors over ℤ2 (Ellerman 2024d).

Ellerman, David. 2021. New Foundations for Information Theory: Logical Entropy and Shannon Entropy. Cham, Switzerland: SpringerNature.

Ellerman, David. 2022. "Introduction to Logical Entropy and Its Relationship to Shannon Entropy." Open Special Issue: Logical Entropy 5 (1): 1–33.

Ellerman, David. 2024a. "A New Logic, a New Information Measure, and a New Information-Based Approach to Interpreting Quantum Mechanics." Entropy Special Issue: Information-Theoretic Concepts in Physics 26 (2).

Ellerman, David. 2024b. Partitions, Objective Indefiniteness, and Quantum Reality: The Objective Indefiniteness Interpretation of Quantum Mechanics. Cham, Switzerland: Springer Nature.

Ellerman, David. 2024c. "A Fundamental Duality in the Exact Sciences: The Application to Quantum Mechanics." Foundations 4 (2): 175–204.

Ellerman, David. 2024d. "A New Approach to Understanding Quantum Mechanics: Illustrated Using a Pedagogical Model over ℤ2." AppliedMath 4 (2): 468–94.

Matteo Fadel (ETH Zürich, Switzerland)

Title: Probing Spacetime with Mechanical Oscillators

Many quantum gravity theories predict a discrete structure of spacetime, particularly at the Planck scale, which can manifest as deformations of the canonical Heisenberg uncertainty principle and corresponding modifications to the commutation relations between position and momentum operators. This fundamental granularity of spacetime may be inherently time-dependent, leading to modifications in the time evolution of quantum systems. In particular, I will discuss the consequences of such time-dependent deformations for quantum superpositions, showing that they induce a novel source of decoherence in the spatial superpositions of massive systems. This decoherence arises not from environmental interactions, but from intrinsic fluctuations in the underlying foam-like spacetime geometry. I then demonstrate how state-of-the-art mechanical oscillators, especially those with high mass and long coherence times, can serve as probes of this predicted effect. By mapping the influence of deformed commutators onto the observable dynamics of these systems, I will identify

experimentally accessible regimes in which the fundamental structure of spacetime could be tested. This approach opens a new pathway to empirically constrain quantum gravity theories using low-energy, tabletop opto- and electro-mechanical systems.
[1] Sandro Donadi and Matteo Fadel, Phys. Rev. D 111, 026009 (2025).
[2] Matteo Fadel et al. (in preparation)

José Luis Gaona Reyes (University of Trieste, Italy)
Title: About the operational distinction of different unravelings
I will address recent suggestions about the operational distinction between different unravelings of a given master equation. I will argue that the quantities which allow a distinction between different unravelings can be computed once the measurement procedure is given, so there cannot be an operational distinction when the procedure is unknown. I will also discuss a connection between the operational unraveling distinction and superluminal communication protocols.

Masoud Gharahi (University of Trieste, Italy)
Title: Entangled Subspaces through Algebraic Geometry
We propose an algebraic geometry-inspired approach for constructing entangled subspaces within the Hilbert space of a multipartite quantum system. Specifically, our method employs a modified Veronese embedding, restricted to the conic, to define subspaces within the symmetric part of the Hilbert space. By utilizing this technique, we construct the minimal-dimensional, non-orthogonal yet Unextendible Product Basis (nUPB), enabling the decomposition of the multipartite Hilbert space into a two-dimensional subspace, complemented by a Genuinely Entangled Subspace (GES) and a maximal-dimensional Completely Entangled Subspace (CES). In multiqudit systems, we determine the maximum achievable dimension of a symmetric GES and demonstrate its realization through this construction. Furthermore, we systematically investigate the transition from the conventional Veronese embedding to the modified one by imposing various constraints on the affine coordinates, which, in turn, increases the CES dimension while reducing that of the GES.

Anirudh Gundhi (University of Trieste, Italy)
Title: Measuring decoherence due to vacuum fluctuations
The existence of zero-point modes, or the so-called vacuum fluctuations, is one of the fundamental predictions of quantum field theory. From an open quantum system perspective, they constitute an omnipresent and an unavoidable environment of a charged particle. In this talk I would like to discuss if such an environment can lead to observable decoherence and compare it with fundamental decoherence predicted by models of wavefunction collapse.

Onur Hosten (Institute of Science and Technology Austria, Austria)
Title: Control, sensing and gravitational coupling of milligram pendulums: towards interfacing quantum and gravity
Can we test the quantum mechanical nature of gravitational fields? Milligram-scale optomechanical experiments present a frontier for bridging quantum mechanics and gravitational physics by aiming to strike a balance between 1) making gravitational couplings of the controlled objects dominant and 2) making the motions of these objects quantum noise dominated. Required systems necessitate low-frequency dynamics that is typically considered quantum-unfriendly, but seems to be needed to achieve a large figure-of-merit in the problem, quantifying the ability to generate quantum

entanglement gravitationally. In this talk, I will first focus on our 1-milligram suspended torsional pendulum operating at 18 Hz, and the successful laser cooling of its motion to 240~microkelvins. I will elucidate the resulting boost in the quantum coherence length of this pendulum, benchmarking a state-of-the-art quantum-gravity figure-of-merit with a vast improvement potential [1]. I will outline a realistic path to enter a regime where gravitational entanglement could be generated utilizing our zig-zag optical cavities [2] to boost the interactions of light and torsional pendulums. I will conclude with the ongoing effort of achieving gravitationally-limited coupling between two free running ~1 milligram pendulums – aiming to push observable inter-particle gravitational couplings down by 3 orders of magnitude relative to current state of the art.
[1] "1-milligram torsional pendulum for experiments at the quantum-gravity interface", S. Agafonova, P. Rossello, M. Mekonnen, O. Hosten, arXiv:2408.09445 (2024).
[2] "A zigzag optical cavity for sensing and controlling torsional motion", S. Agafonova, U. Mishra, F. Diorico, and O. Hosten, Phys. Rev. Research 6, 013141 (2024).

Kinjalk Lochan (IISER Mohali, India)
Title: <u>Recent Advancements in cavity controlled Quantum Field effects</u>
The idea of judicious selection of boundary conditions has been recently advanced to meaningfully enhance some low cross section quantum field theoretic events. In this talk, we will discuss some recent proposals of proper selection of mode functions to identify and amplify many interesting effects like acceleration radiation, Unruh thermality, Entanglement harvesting and Field-Field interactions. Such studies advocate the idea of achieving precision boundary conditions as a potential replacement of extreme conditions in the attempts of realizing these interesting theoretical predictions.

Giuseppe Antonio Nistico' (University of Calabria, Italy)
Title: <u>Classicality enforced by consistent value assignments</u>
In this talk I show an alternative approach to the problem of the emergence of classicality. This problem comes from the fact there was always evidence that at a macroscopic level world behaves according to classical physical laws rather than to quantum laws. Then the universality of quantum theory requires that this emergence be derived according to quantum laws. The literature provides us with a rich collection of proposals to answer the question. An early approach consisted in verifyng that classicality emerges in the limit h->0. In other approaches classicality derives from 'decoherence': under suitable circumstances, spontaneous or stimulated collapse of the quantum state takes place, and a classical behaviour emerges.
Our alternative approach is based on the following two validated remarks. (1) Non-classicality of quantum physics originates from the empirical ascertainment that each specimen of the physical system is not always assigned a value of every magnitude, as an objective property of that specimen. (2) But in some circumstances this limitation to a simultaneous assignment can be consistently overcome by making use of ``evaluations", a quantum concept investigated in [Int.J.Theor.Phys. Vol. 55 1798].
The essential strategy of the approach is to extend the concept of evaluation in such a way that it can be applied to the observables describing a phenomenon that exhibits classicality, such as the motion of the center of mass of a macroscopic body. In this case classicality consists in the simultaneous consistentvalue assugnment to the position and the velocity of the center of mass, which are non-commuting quantum observables. The work proves that evaluations exist which realize a consistent

value assignment to both these observables. Thus in this caseclassicality is derived from the possibility of otflankingthe quantum limits to a consistent value assignment to non-commuting observables.
Reference: arXiv, https:\\arxiv.org\abs\2412.07453.

Emanuele Panella (University College London, UK)
Title: Hybrid classical-quantum steady states
We will consider coupled oscillators in the hybrid classical-quantum formalism, including decoherence and diffusion effects in a consistent manner. We will discuss under which conditions the dynamics of the combined system reaches a steady state, solve for it explicitly and analyse its properties.

Mauro Paternostro (University of Palermo, Italy)
Title: Learning your quantum environment
Spectral densities encode the relevant information characterising the system-environment interaction in an open-quantum system problem. Such information is key to determining the system's dynamics. In this talk, I will leverage the potential of machine learning techniques to reconstruct the features of the environment. Specifically, I will show that the time evolution of a system observable can be used by an artificial neural network to infer the main features of the spectral density. In particular, for relevant examples of spin-boson models, I will show the successful classification, with high accuracy, of the Ohmicity parameter of the environment, thereby distinguishing between different forms of dissipation. I will then discuss how, For a dissipative spin-boson model with a structured spectral density expressed as a sum of Lorentzian peaks, the time evolution of a system observable can be used by a neural network to classify the spectral density as comprising one, two, or three Lorentzian peaks and accurately predict their central frequency, thus providing a detailed description of the spectral density itself.

Nicolò Piccione (University of Trieste, Italy)
Title: Hybrid Classical-Quantum Newtonian Gravity with stable vacuum
I will present the Gravitational Poissonian Spontaneous Localization (GPSL) model, a hybrid classical-quantum model in which classical Newtonian gravity emerges from stochastic collapses of the mass density operator, and consistently couples to quantum matter. Unlike models based on continuous measurement schemes, GPSL ensures vacuum stability; this, together with its applicability to identical particles and fields, makes it a promising candidate for a relativistic generalization. I will present an analysis of the model's general properties, and compare its predictions with those of the Tilloy-Diósi models. Notably, GPSL predicts a short-range gravitational back-reaction and permits decoherence rates below the Diósi-Penrose bound, thereby evading the "Principle of Least Decoherence".

Ricardo Puebla (Universidad Carlos III de Madrid, Spain)
Title: Mean-field critical systems: Irreversibility and breakdown of Kibble-Zurek mechanism
Quantum phase transitions are known to take place in distinct interacting many-body systems. They offer an excellent testbed to explore fundamental aspects of out-of-equilibrium dynamics and how such critical features impact thermodynamic quantities, such as work and entropy. The Kibble-Zurek mechanism is of the most significant results in this regard, as it successfully predicts universal scaling

laws for the amount of excitations when a critical point is traversed at a finite rate. Yet, mean-field critical systems challenge this notion. In the strict thermodynamic limit, the effective model reduces to a simple harmonic oscillator. A finite-time cyclic protocol reaching the critical point results in a constant amount of squeezing, which leads to a non-zero irreversible work even in the limit of an infinitely slow cycle, thereby breaking the Kibble-Zurek scaling. Owing to the simplicity of the model, both the full work probability distribution and irreversible entropy can be characterized. This allows us to pinpoint the role that quantum coherence plays in entropy production.

W. Mark Stuckey (Elizabethtown College, USA)
Title: Completing the Quantum Reconstruction Program via the Relativity Principle
The popular view in quantum foundations is that quantum entanglement leads to tension, if not an outright contradiction, between special relativity and quantum mechanics. In this talk, I will explain how these two theories go beyond "peaceful coexistence", as they can both be understood as "principle theories" (per Einstein) based on empirically discovered facts justified by the relativity principle. Specifically, I will show how the axiomatic reconstruction of quantum mechanics based on the information-theoretic principle of Information Invariance and Continuity entails the observer-independence of Planck's constant h between inertial reference frames related by spatial rotations and translations. This is in total analogy to the observer-independence of the speed of light c between inertial reference frames related by boosts. Obviously, these empirically discovered facts can both be justified with the relativity principle, as Einstein did with the latter. The conclusion is that quantum mechanics and special relativity can both be considered principle theories based on empirically discovered facts justified by the relativity principle. Accordingly, the quantum reconstruction program can be completed with the relativity principle.

Anderson Tomaz (Aix-Marseille University, France)
Title: Gravitationally-induced wave function collapse time for molecules
The Diósi–Penrose model states that the wave function collapse ending a quantum superposition occurs due to the instability of coexisting gravitational potentials created by distinct geometric conformations of the system in different states. The Heisenberg time-energy principle can be invoked to estimate the collapse time for the energy associated with this instability, the gravitational self-energy. This paper develops atomistic models to calculate the Diósi–Penrose collapse time. It applies them to a range of systems, from small molecules to large biological structures and macroscopic systems. An experiment is suggested to test the Diósi–Penrose hypothesis, and we critically examine the model, highlighting challenges from an atomistic perspective, such as gravitational self-energy saturation and limited extensivity.

Hendrik Ulbricht (University of Southampton, UK)
Title: Levitated mechanical detector for Dark Matter
We will discuss three options for using levitated mechanics to detect ultra-low mass dark matter (ULDM) such as axion-like particle (ALPs). If time permits, we will also discuss a way to use mechanical rotors to amplify electromagnetic fields.

Andrea Vinante (CNR Trento, Italy)
Title: Magnetic spinning rotors as a new platform for precision tests in fundamental physics

I will present an initial investigation of ultrafast spinning rotors based on ferromagnetic microspheres levitated by Meissner effect. At liquid helium temperature and moderate vacuum we achieve rotational speeds above 2 MHz and ultralong damping times above 1E6 seconds. I will discuss the potential of this experimental platform in the context of precision measurements in fundamental physics and some crucial advantages compared to mechanical resonators. Possible applications may include non-interferometric tests of collapse models, measurement of gravity at microscale/high frequency, search for dark matter and tests of rotational quantum field effects.