Book of Abstracts: Poster Section

Emergence of Classicality: New Perspectives on Measurements in Quantum Theory (EoC2024)

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Poster - 01

Laria Figurato (University of Trieste)

On the effectiveness of the collapse in the Diósi-Penrose model

Abstract: 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.

Poster - 02

Soham Sau (RCQI, Institute of Physics, Slovak Academy of Sciences)

Sequential implementation of Quantum Instruments

Abstract: In Operational Quantum Theory, observables are characterized by Positive Operator-Valued Measures (POVMs), which help describe the measurement statistics of an experiment. If the measured system is accessible after the measurement, one might need to tell the post-measurement state along with the measurement statistics. The formalism of Quantum instruments addresses that situation and incorporates the above-mentioned conditions. This is useful when the measured system is utilized to obtain further information or other forms of interaction. Different properties of instruments, like post-processing and incompatibility, have been explored, and it has been theoretically interesting. Also, they have been experimentally characterized.

The work presented is a study of sequential implementation of quantum instruments. We define a property of quantum instruments called 'sequentiality', by which we mean that a single quantum instrument can be realized as an adaptive sequence of quantum instruments. By an adaptive sequence, we mean that every instrument will be dependent upon the classical outcome of the preceding instrument in the sequence. Actually, the sequence is general enough as by the proper choice of the outcome and the choice of the instrument in the sequence, a general instrument of the sequence would depend on all other previous instruments in the sequence.

We provide constructive proof that an instrument can be realized as an adaptive sequence of any finite number of instruments. To be concrete, given an instrument with 'A' being its induced POVM, and if we can post-process 'A' to a POVM 'B', we achieve that the instrument can be realized as a sequence of two instruments: one being a Luders instrument of the POVM 'B' and the other being a non-trivial instrument.

The result extends the knowledge in the area of the foundations of quantum measurement theory in general from the operational point of view and motivates further research to develop the idea of 'sequentiality' in quantum theory.

We consider a special scenario of our case where the outcome space of the instrument is a Cartesian product space. This result can be specifically useful for implementing complex quantum measurements given a limited amount of resources. Specifically, we know that for NISQ (Noisy Intermediate-Scale Quantum) devices, it is essential to reduce the dimension of the ancillary system (reduce spatial resources), and the ideas for the special case of our result enable one to perform a complex quantum measurement through a series of sequential steps, making it a resource-efficient approach and by realizing the measurement sequentially, we tend to lower the implementational complexity of the measurement.

This result has the potential to find an efficient way to perform general sequential measurements, which will give an achievable trade-off between spatial and temporal resources. This method is important in the sense that it is already hard for POVMs to dilate the system in practice and perform measurements in the extended system, and in some, it is quite uncertain whether we could find extra dimensions or not.

POVMs could be considered special cases of quantum instruments. Hence, the idea presented here can be seen as a generalization of the result (PRA 77, 052104 '08), where the sequential implementations of two-outcome POVMs are shown.

Poster - 03

Giuseppe Antonio Nisticò (Università della Calabria - Rende -Italy)

Classical behaviour enforced by Quantum Theory itself

Abstract: A first approach to address the problem of the emergence of classicality consisted in verifyng that the predictions of quantum theory for the expected values have a behaviour obeying classical theories in the limit h-->0 where h is the Planck constant [1]. However, this behaviour holds only for short times and under specific conditions for the initial quantum state. Another approach, avoiding this limitation, is based on the concept of decoherence. According to this approach, also a weak interaction with the environment destroys the superposition, i.e. causes the collapse of a genuine superposition state and a classical behaviour emerges. A different interesting investigation has been pursued [2] showing how the classical trajectories of a particle in a cloud chamber emerge, without making resort to the idea of collapse, but, instead, by a pure quantum theoretical treatment.

The present work gives evidence of a more fundamental theoretical mechanism that determines a classical behaviour as the size of the system grows, in complete agreement with quantum theory. To make clearer the subject, we restrict to the case of a "rigid" body, i.e. a quantum system formed by a large number of identical particles, whose quantum state ψ(rig) satisfies a definite rigidity condition. Non-classicality of quantum theory, in its Hilbert space realization where observables are identified with self-adjoint operators, traces back to the following basic feature: whenever two observables, identified by the self-adjoint operators A and B do not commute, then the same specimen of the system cannot be assigned values a, b for A, B as objective properties of that specimen; in particular they cannot be measured together. The possibility of emergence of classicality for a rigid body is equivalent to the possibility of assigning the same specimen of the body values for the "classical" observabels, e.g. the position of the center of mass q(cm) and its velocity v(cm). In general, the self-adjoint operators Q and V representing these observables do not commute. Therefore the emergence of classicality should be ruled out. Now, by making use of a concept of 'evaluation' introduced in [3] we prove that if A and B do not commute, but the quantum state ψ admits another self-adjoint operator T such that Aψ=Tψ and [T,B]=0, to assign A the value obtained for T in a simultaneous measurement of T and B is consistent with all actually performed measurements and with all predictions of quantum theory.

The consistency of this value assignment depends on the quantum state ψ. We prove that the condition of rigidity for our body implies that a self-adjoint operator T exists such that Tψ(rig)=V(cm)ψ(rig). Therefore, a system of a large number of particles can be consistently assigned both the values of the position (directly measured) and of the velocity (evaluated by measuring T) of its center of mass, if its quantum state characterizes the system as a rigid body. Thus, classicality is enforced by quantum theory itself.The argument can be extended to more general sets of classical observables.

[1] Robert D. Helv.Phys.Acta, 71 44

[2] Teta A. Eur.J.Phys. 31 215

[3] Nisticò G., Sestito A. Int.J.Theor.Phys. 55:1798–1810

Poster - 04

Oisín Culhane (Trinity College Dublin)

Powering an autonomous clock with quantum electromechanics

Abstract: We theoretically analyse an autonomous clock comprising a nanoelectromechanical system, which undergoes self-oscillations driven by electron tunnelling. The periodic mechanical motion behaves as the clockwork, similar to the swinging of a pendulum, while induced oscillations in the electrical current can be used to read out the ticks. We simulate the dynamics of the system in the quasi-adiabatic limit of slow mechanical motion, allowing us to infer statistical properties of the clock's ticks from the current auto-correlation function. The distribution of individual ticks exhibits a tradeoff between accuracy, resolution, and dissipation, as expected from previous literature. Going beyond the distribution of individual ticks, we investigate how clock accuracy varies over different integration times by computing the Allan variance. We observe non-monotonic features in the Allan variance as a function of time and applied voltage, which can be explained by the presence of temporal correlations between ticks. These correlations are shown to yield a precision advantage for timekeeping over the timescales that the correlations persist. Our results illustrate the non-trivial features of the tick series produced by nanoscale clocks, and pave the way for experimental investigation of clock thermodynamics using nanoelectromechanical systems.

Poster - 05

José Antonio Almanza Marrero (IFISC (Institute for Cross-Disciplinary Physics and Complex Systems))

Quantum-thermodynamic enhancements in continuous \\ thermal machines require energetic coherence

Abstract: Quantum coherence has been shown to impact the operational capabilities of quantum systems performing thermodynamic tasks in a significant way, and yet the possibility of genuine coherence-enhanced thermodynamic operation remains unclear. Here we show that only the presence of energetic coherence ---coherence between levels with different energies--- in steady-state quantum thermal machines can lead to genuine thermodynamic advantage. On the other hand, engines showing coherence between degenerate levels, or subjected to noise-induced coherence, are shown to be systematically outperformed by classical stochastic engines using exactly the same set of (incoherent) resources. We illustrate our results with three prototypical models of heat engines and refrigerators and employ multi-objective optimization techniques to characterize quantum-enhanced regimes in connection with the thermodynamic uncertainty relation.

Poster - 06

Pablo Martinez Azcona (University of Luxembourg)

Stochastic Non-Hermitian Hamiltonians

Abstract: Non-Hermitian Hamiltonians display striking phenomena unique to open quantum systems. We study the fate of the dynamics when the non-Hermitian Hamiltonian is subject to a stochastic perturbation in its anti-Hermitian part. The noise-averaged dynamics is described by a non-trace preserving master equation beyond Lindblad form for which we derive the short-time decoherence rates. We introduce a general theory for steady states and their stability for non-trace preserving Liouvillians. Applying this general formalism we characterize the possible dynamics, which include purification, decoherence-free subspaces, and dephasing, and illustrate them in the stochastic dissipative Qubit.

Poster - 07

Luca Previdi (University of Bologna)

OH molecule as multi-parameter quantum probe of static electric and magnetic fields

Abstract: The study of the hydroxyl (OH) molecule in its ground state has emerged as a cornerstone in advancing the fields of ultracold chemistry and quantum computing, among others. The unique significance of the OH molecule is attributed to its inherent electric and magnetic dipole moments coupled with a diatomic structure that simplifies theoretical modeling. This simplification has paved the way for the development of a specialized basis conducive to the explicit formulation of Hamiltonians for diatomic molecules under the influence of static electric and magnetic fields. A pivotal aspect of utilizing the OH molecule in these cutting-edge applications lies in the precise estimation of parameters characterizing the external fields acting upon it. This precision is paramount for harnessing the molecule's full potential in technological applications.

This publication delves into the application of Local Quantum Estimation Theory (QET) to devise strategies aimed at accurately determining the values of external fields acting on the OH molecule and decoding its behavior under such influences. By leveraging QET, we have been able to exploit non-classical features of the system, facilitating the attainment of optimal precision in parameter estimation. Our exploration encompasses a broad spectrum of physically relevant scenarios, presenting both analytical and numerical analyses to identify the most effective strategies for precision enhancement in parameter estimation.

In the initial segment of our investigation, we concentrate on scenarios where the fields are aligned, enabling a thorough analytical examination. This analysis yields optimal measurement strategies for both the ground state of the system and an arbitrarily chosen pure state. Subsequently, we extend our focus to the complete system. Beginning with the ground state, we undertake a numerical analysis to unravel the information it offers about the parameters, subsequently identifying optimal measurement strategies. Among these strategies, we distinguish those most resilient to thermal noise.

The investigation further considers thermal states, optimizing estimation strategies both pre and post-thermalization. We examine two distinct cases: one involving a Gibbs state, characterized by parameter dependencies emerging from unitary evolution, and another involving a static probe, where the information regarding the fields is inherently encoded in the quantum state's configuration.

Moreover, we explore schemes for optimal controlled evolution aimed at restoring the quadratic temporal dependency of information relative to the parameters, including optimization of the probe within this framework. In a progression towards practical application, we assess scenarios incorporating adaptive controls based on initial parameter estimations. This assessment addresses the efficacy of adaptive strategies compared to multiple measurement approaches, especially in terms of the accuracy of estimators relative to the true parameter values.

While our study specifically applies to the OH molecule system, the characterization of adaptive strategies presented herein remains universally applicable across different systems. This comprehensive analysis not only advances our understanding of quantum estimation in the context of the OH molecule but also lays a foundational framework for the application of these principles in broader quantum technological pursuits.

Poster - 08

Shushmi Chowdhury (University of Glasgow)

From Path Integrals to Quantum Observables: Exploring Weak Measurements

Abstract: Weak measurements continue to bring new insights into quantum mechanics since their inception [1], giving rise to phenomena such as discontinuous trajectories in nested Mach-Zehnder interferometers [2]. Using path integral formalism, weak values can be mathematically derived, further supporting experimental signatures [3].

We investigate weak measurements through the path integral framework, focusing on the possible paths that particles traverse within a nested Mach-Zehnder interferometer. Our study encompasses two distinct scenarios: the first examines photons as measuring devices via their projection operators, and the second explores mirrors as probes, resorting to an optomechanical treatment of the mirrors. We extend the path integral approach for weak values [3] to a sequence of weak measurements and study the probe shifts across the different branches of the interferometer. Since all photons are part of the same ensemble, with both measurement and post-selection coming from the same photon ensemble, they become a more practical choice for the pointer. However, this also makes it challenging to mathematically distinguish the shifts a photon experiences in subsequent measurements, due to the inherently weak nature of the interactions. In a nested Mach-Zehnder interferometer, considering an inner setup where a photon has two potential paths, labeled as E→A→F and E→B→F, it's theoretically feasible for the shifts induced by mirrors E and F (positioned at the entrance and exit of the inner interferometer, respectively) on the photon's Gaussian pointer to effectively cancel out at the point of recombination, depending on the precise alignment and configuration of the interferometer. As reported by [2], the surprising result comes about when the inner interferometer is tuned to have the beam destructively interfere at the post-selected detector. With this setting, the weak values suggest photon presence in the inner interferometer despite the 'which-way' paths of the inner interferometer not reaching the detector. This is justified using the two-state vector formalism, with both the post- and pre-selected states needing to be present to explain this discontinuity. Nevertheless, using mirrors as probes within an optomechanical setup—coupling the optical field with oscillating mechanical mirrors—offers an alternative theoretical analysis for "which-way" analysis, despite significant experimental challenges. We detail how optomechanical probing enables the simultaneous independent weak measurement of mirror states, provided there is no correlation between the mirrors. Sequential weak measurements in the interferometer can be used to explore the effects of subsequent weak projections on the system and further open avenues for exploring the evolution of weak values in open quantum systems. Path integrals facilitate understanding the emergence of the semi-classical limit from within the distinct families of quantum paths in the interferometer branches; enabling us to comprehend the quantum nature of propagation within the entire family of paths. Our study aids in bridging the gap between quantum foundations and experimental applications, enhancing our understanding of fundamental physics through a theoretical framework.

[1] Aharonov, A. et al. (1988) 'How the result of a measurement of a component of the spin of a spin-1/2 particle can turn out to be 100', Physical Review Letters, 60(14), 1351–1354. https://doi.org/10.1103/physrevlett.60.1351.

[2] Danan, A. et al. (2013) ‘Asking photons where they have been’, Physical Review Letters, 111(24). doi:10.1103/physrevlett.111.240402.

[3] Matzkin, A. (2020) 'Weak values from path integrals', Physical Review Research, 2(3). https://doi.org/10.1103/physrevlett.2.032048.

Poster - 09

Saulo Vicente Moreira (Trinity College Dublin)

Precision bounds for multiple currents in open quantum systems

Abstract: Thermodynamic (TUR) and kinetic (KUR) uncertainty relations are fundamental bounds constraining the relative fluctuation of observables in terms of dissipation or dynamical activity in classical, non-equilibrium systems. Several works have verified, however, violations of these classical bounds in open quantum systems, indicating that they are not suitable to constrain the relative fluctuation of observables when quantum dynamics is involved. To address this, new quantum TURs and KURs have been recently derived in the literature for single observables. Here, we build on previous works and derive multidimensional KUR and TUR for multiple observables in open quantum systems using a multi-parameter metrology approach. Crucially, our bounds are tighter than previously derived quantum TURs and KURs for single observables, because they incorporate correlations between multiple observables. By considering two examples, namely a coherently-driven qubit system and the three-level maser, we demonstrate that the multidimensional quantum KUR bound can even be saturated when the observables are strongly correlated.

Poster - 10

Guoyong Xiang (University of Science & Technology of China)

Experimental Optimal Quantum State Estimation with Genuine Three-copy Collective Measurements

Abstract: Nonclassical phenomena tied to entangled states are focuses of foundational studies and powerfulresources in many applications. By contrast, the counterparts on quantum measurements are stillpoorly understood. Notably, genuine multipartite nonclassicality is barely discussed, not to say experimental realization.

In this work, we explore genuine tripartite nonclassicality in quantum measurements and experimentally demonstrate its information-extraction power based on a simple estimation problem. More specifically, we consider the estimation of a random qubit pure state given three identically prepared copies. We first choose a genuine three-copy collective measurement that is optimal for the estimation task and is strictly better than alternative choices based on restricted collective measurements assisted by adaptive strategies. Surprisingly, however, GME is not involved in any POVM element associated with this optimal measurement, which reveals a subtle distinction between quantum measurements and quantum states with regard to multipartite nonclassicality. Then we experimentally realize this genuine collective measurement with a high quality via a nine-step twodimensional (2D) photonic quantum walk featuring 30 elaborately designed coin operators. Based on this measurement we realize an optimal estimation protocol and achieve an unprecedented high estimation fidelity. Notably, the estimation fidelity we achieved significantly outperforms the upper bound for strategies based on restricted collective measurements, which demonstrates the true realization of a genuine three-copy collective measurement and its power in quantum state estimation.

These results clearly demonstrate that genuine collective measurements can extract more information than local measurements and restricted collective measurements. Our work opens the door for exploring genuine multipartite nonclassical measurements and their power in quantum information processing.

[1] Kai Zhou Changhao Yi, Wen-Zhe Yan, Zhibo Hou∗, HuangjunZhu†, Guo-Yong Xiang ‡, Chuan-Feng Li, and Guang-Can Guo, arXiv:2312.01651

Poster - 11

Antoine Soulas (Université de Rennes)

Two universal models for the theory of decoherence

Abstract: The theory of decoherence is arguably one of the greatest advances in fundamental physics of the past forty years. Since the pioneering papers, a wide variety of models have been designed to understand decoherence in different specific contexts. In this talk, however, we would like to embrace a more general point of view, and address the two following questions as universally as possible, i.e. without specifying any Hamiltonian:

1. What is the typical size of an environment needed to entail proper decoherence on a system?

2. Why is the universe not frozen by the quantum Zeno effect?

For the fisrt one, we start by introducing general quantities and notations to recall as concisely as possible the idea underlying the theory of decoherence. We then build a simple but very general model for a purely random environment, which reveals the mathematical mechanisms that make decoherence so universal. First, the well-known typical decay (already obtained by Zurek in the 80s) of the non-diagonal terms of the density matrix in 1/√n is recovered, with n the dimension of the Hilbert space describing the environment. The most important result is a theorem, giving quantitative estimates for the level of decoherence induced by a random environment on a system of given sizes. We conclude that even very small environments (of typical size at least N_E = \ln(N_S) with N_S the size of the system) suffice, which is not good news for quantum computing... The (strong) assumptions of the model are discussed in the end of the talk, but possible improvements lead to interesting directions of research, in particular trying to describe the submanifold of truly reachable states in the Hilbert space, a question that could possibly be answered using the tensor networks theory and the area law for entanglement entropy. Finally, we propose other ways to quantify decoherence, as well as a general formula estimating the level of classicality of a quantum system in terms of the entropy of entanglement with its environment.

For the second question, we present a discrete model that formalizes the competition between free evolution and decoherence. An analytic criterion is derived, depending on the level of short time decoherence, that allows to determine whether the system will freeze due to the Zeno effect. We check this criterion on several classes of function, corresponding to different physical situations. In the most generic case, we explain why the free evolution wins over the Zeno effect, explaining why the universe is indeed not frozen.

Poster - 12

Darren Moore (Palacky University)

Nonlinear Squeezing in Classical and Quantum Mechanics

Abstract: For quantum continuous variables, conventional squeezing in linear combinations of the canonical variables is a fundamental sign of nonclassical behaviour. However, it cannot distinguish Gaussian states from non-Gaussian ones. Motivated by the short time effects of nonlinear potentials such as the cubic potential, we describe squeezing in a nonlinear combination of variables that can be leveraged to detect non-Gaussian states, called nonlinear squeezing [1]. The resulting thresholds are detectors of quantum non-Gaussianity, in that they also exclude incoherent mixtures of Gaussian states. The scheme relies on collecting statistics of position and momentum quadratures (homodyne detection) and is thus amenable to experiment. We present a scheme to detect this nonlinear squeezing in an optomechanical setting [2]. Additionally, we show that the concept is fruitful even in classical mechanics where, analogous to the detection of quantum non-Gaussianity, nonlinear squeezing acts as a detector of genuinely nonlinear behaviour [3]. That is, statistics below a given threshold cannot be achieved using up-to-quadratic potentials operating in environments at fixed temperature. This connects the classical and quantum pictures, as at low enough temperatures the quantum mechanical threshold must dominate. We mainly focus on the cubic potential as an exemplar, however this potential is unbounded, an unphysical situation that will not occur in any real experiment. To approach a remedy for this situation we briefly examine the effect of weakly bounding cubic potentials with a quartic potential in the short time approximation (cubic and quartic gates) and show that this bounding tends to degrade the nonlinear squeezing. In the process, we show how to calculate the effect of quartic bounded cubic phase gates on the Wigner function. This allows us to demonstrate analytically that the negativity of the Wigner function survives no matter the initial Gaussian thermal noise [4].

[1] D. W. Moore, R. Filip Commun. Phys 5, 128 (2022)

[2] D. W. Moore, A. A. Rakhubovsky, R. Filip New J. Phys. 21 113050 (2019)

[3] L. Ornigotti, D. W. Moore, R. Filip New J. Phys. 26 013022 (2024)

[4] D. W. Moore, R. Filip (submitted to NPJ QI)

Poster - 13

Prabhav Jain (TU Darmstadt)

Information causality as a tool for bounding the set of quantum correlations

Abstract: Characterising the set of quantum correlations in the space of all possible non-signalling theories is a hard but important problem. For a given Bell scenario, quantum bell inequalities such as the Tsirelson's bound on the CHSH expression and the Uffink's inequality have been derived to bound the set of quantum correlations. Such inequalities are relevant not only as a theoretical interest but for several applications such as QKD and the certification of quantum devices. A fundamental goal is to 'derive' this quantum set from physical principles without assuming any of the underlying formalism. In this work, we use information causality (IC) as one such physical principle. This principle is one among the many approaches such as Macroscopic Locality, Local Orthogonality, Non-trivial Communication Complexity and Almost Quantum Correlations all of which try to bound the space of quantum correlations without assuming any of its formalism. IC, as the name suggests, is an information theoretic principle and is usually formulated in the context of guessing games such as random access codes. Suppose we have Alice and Bob which are spacelike separated. Alice receives two bits {a_0, a_1} and Bob receives a single bit b= 0,1. Bob's goal is to guess Alice's b-th bit. To achieve that, both of them are allowed to share a randomness resource and Alice can also send a single bit message to Bob. The statement of IC now states that the mutual information between Alice's bits and Bob's guess is bounded by the capacity of the communication channel. What this essentially means is that the amount of information potentially available to Bob about Alice's data cannot be higher than the amount of information Alice sends to him.

In the original paper, IC was famously shown to reproduce Tsirelson's bound of the CHSH inequality and the Uffink's inequality that approximates the set of quantum correlations. This result found limited generalisations due to the difficulty of deducing implications of the IC principle on set of correlations. In this work, we take a significant step forward in using IC to bound the set of quantum correlations. We present a simple technique for deriving polynomial inequalities from IC, bounding the set of physical correlations in any Bell scenario.

To demonstrate our method, we derive a family of inequalities which non-trivially constrain the set of non-local correlations in Bell scenarios with binary outcomes and equal number of measurement settings. As an application of the above inequalities, we analytically obtain a non-trivial bound for the so-called I_{nn22} inequalities. Except for some quantum Bell inequalities which follow directly from the formalism of QM there is no general technique to analytically obtain such upper bounds on quantum violation of Bell inequalities. The only alternative approach that we are aware of, corresponds to the Macroscopic Locality principle which is known to be weaker than IC in specific Bell scenarios.

Finally, we propose an improved statement of the IC principle. We demonstrate it by modifying the original scenario of the guessing game so that the inputs of Alice are now correlated. In particular, applying our algorithm to this modified scenario, we are able to obtain a quantum Bell inequality that is tighter than the Uffink's inequality in the simplest Bell scenario and exactly recovers a part of the boundary of the quantum set.

The current work opens new possibilities of working with physical principles that are based on communication scenarios. It is interesting to see if tighter quantum Bell inequalities, which include one-point correlators, can be ever obtained from the IC principle or its generalisations. Another interesting open question is to study the relation between information causality and almost quantum correlations set and the implications of information causality on communication complexity.

Based on arXiv:2308.02478

Poster - 14

Jiaxuan Zhang (University of Oxford)

Compatible Complexity for n-dimensional Quantum Measurements

Abstract: Measurement incompatibility is one of the key concepts in quantum physics, which was first articulated in the famous Uncertainty Principle (Heisenberg, 1927). Traditionally, measurement compatibility has been understood in terms of commuting observables. While commutativity relationships are sufficient for characterizing compatibility for projective measurements, the latter does not exhaust the most general process. For general quantum measurements, represented by positive-valued operator measures (POVMs), a broader notion of compatibility is necessary, and non-commuting measurements can still be compatible. Compatible measurements allow for classical memory instead of quantum memory in experiments. However, more measurement outcomes increase the difficulty of implementing the measurement in practice. Thus, reducing the complexity for compatible families of POVMs is important from the application point of view.

Despite the large amount of works studying the compatible complexity of qubit measurements (Bavaresco et al., 2017; Skrzypczyk et al., 2020; Zhang et al., 2023), relevant research on higher dimensions is rare. In this work, we study the compatibility complexity for the n-dimensional POVMs, especially the qutrit case. We are interested in how noisy a n-dimensional quantum system must be before all measurements performed on it become compatible.

We adopt the notion of joint measurability for compatibility. A family of POVMs is joint measurable if and only if there exists some ''parent'' measurement that, with some classical processing, can substitute the function of the family of compatible ''children'' measurements (Skrzypczyk et al., 2020). We consider two definitions of the parent POVM: the canonical parent involves only coarse-graining of measurement outcomes, and the probabilistic parent allows for a stochastic processing of the outcomes. Both forms lead to equivalent properties of whether a family of POVMs is compatible (Skrzypczyk et al., 2020). However, the sizes of parent POVMs are usually sufficiently smaller in the latter case.

We use canonical parents for families of dichotomic and trichotomic children to find lower bounds. By verifying the positivity constraint for these parents, we establish lower bounds for arbitrary cross-sections of the qutrit and ququart measurement space. Our method can be directly applied to higher dimensions. We also adopt the geometric method for finding lower bounds for planar qubit measurement from previous work (Zhang et al., 2023), expanding the results to the qutrit case.

For upper bounds, we use semidefinite programming (SDP) adjusted from previous works (Bavaresco et al., 2017; Zhang et al., 2023) to simulate dichotomic or trichotomic planar children POVMs. We prove the parent POVMs with the longest Bloch vectors are optimal for simulating larger families of children POVMs. Our results show that trichotomic children behave better in finding lower bounds, while dichotomic children behave better in finding upper bounds.

Our study offers novel analyses of compatibility complexity in quantum measurements beyond the 2-dimensional qubit systems. Our results can facilitate many quantum operations requiring measurement incompatibility, like quantum steering (Uola, 2020). Since the noise between the state and measurements can be exchanged, studying the robustness of incompatible measurements also helps us learn about the noise the states can tolerate during transmission. There are increasing number of groups working on implementing quantum computation using qutrits (Gokhale, 2020; Blok, 2021; Roy, 2023). Understanding the properties of higher dimensional quantum measurement will allow us to expand the applications and enhance our understanding of quantum phenomena.

Poster - 15

Krissia Zawadzki (University of São Paulo)

Using entanglement to shape the work statistics

Abstract: In quantum systems, work is not associated with an observable, but with a distribution probed in a two-point measurement scheme (TPM). By increasing the number of particles, the work distribution is expected to display a Gaussian profile, resembling classical systems in the thermodynamical limit. Gaussian work distributions have been observed in various many-body systems after sudden quenches across the critical point. It is natural to understand this result, as the number of eigenstates scales with the system size and, consequently, more transitions are captured by the TPM. Only more recently, it has been shown that Gaussianity is lost if the work protocol is carried out at finite times [Phys Rev A 107.012209, 2023] or in special correlation regimes that forbid some transitions to occur [Phys Rev Research 2.033167, 2020]. One can then imagine a protocol that manipulates correlations to shape the work statistics. Here, we demonstrate such a protocol in a fermionic system undergoing the superfluid-to-insulator transition [Adv. Quantum Technol. 2300237, 2024]. We show that if the initial ground-state has minimum entanglement, the average absorbed work is maximized at the criticality, whilst its variance is minimized at the same rate in which fluctuations in density-density correlations decay. Features of the quantum phase transition are suppressed when the temperature is increased, and we observe that thermal fluctuations favor work extraction (instead of absorption) whenever thermal excitations become larger than the typical energy scales of the system.

Poster - 16

Danilo Micali Fucci (Departamento de Física, Universidade Federal do Paraná)

Theory-Independent Realism

Abstract: Realism usually refers to the definiteness of the physical properties of a system at any instant in time, regardless of the influence of observers. Once scientific knowledge's purpose is to convey relevant information about what lies beyond our senses, it is reasonable to expect a physical theory to be consistent with the assumption of realism. That is the case for classical theories, but the predictions of quantum theory invite us to question this assumption. Realism's seminal definition for the context of physics was developed by Einstein, Podolsky, and Rosen (EPR), called elements of reality, without which the first hint at nonlocal characteristics of the theory would not be possible. The literature advanced with new proposals put forward, like the one by Fine [1], relating realism with the assignment of joint probabilities to the measurement of physical properties. Fine's formulation highlights realism and incompatibility's conflict. Bilobran and Angelo (BA) devised a criterion based on the rationale that whenever a physical property is measured, it becomes real, regardless of whether the outcome was observed [2]. The assumption that a measurement has the property of establishing realism is directly tied to the measurement problem, or what makes a measurement a measurement [3]. A deeper understanding of realism in itself is sure to bring new insights into these foundational subjects. This work [4] investigates realism beyond the scope of quantum mechanics. BA's proposal inspires us to come up with a realism criterion that relies solely on the probabilities assigned to the outcomes of measurements of physical properties in a physical state, but is independent of the rules that dictate those probabilities. The framework of generalized probabilistic theories (GPT) [5] paves our way for the description of states, measurements, and transformations in such a general context. A theory-independent incursion is hoped not only to bring insight into quantum mechanics and its relation with other physical theories, but also to provide a framework suited for physical theories still to be developed. Our criterion's core idea follows the intuition that, in a realist theory, if a measurement is performed, but its outcome is not revealed, the measurement is inconsequential. Thus, we demand that for a specific physical property to be real given a physical state, the probabilistic profile governing the outcomes of measurements for any other physical property should be unchanged if that physical property was measured beforehand. Two deviance measures for this criterion were designed, giving two irrealism, realism's counterpart, quantifiers. The first employs the concept of robustness, quantifying the minimal amount of mixing a state that is irrealist for a physical property requires for that property to become real. The second implements the Kullback-Leibler divergence, measuring the distance between the probability distributions characterizing the states before and after the measurement protocol of a physical property. For both quantifiers, a case study was conducted for qubit systems. Our findings reveal that our criterion generalizes both BA's and Fine's, behaving as expected for quantum and classical mechanics. The case study involving our irrealism quantifiers shows that they are not equivalent to BA's irrealism, but behave similarly, with concordant minima, maxima, and monotonically crescent parametric plots.

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Poster - 17

Ardra Ajitha Vijayan (RCQI Bratislava, Institute of Physics, Slovak Academy of Sciences, Comenius University)

Activating strong nonlocality from local sets: An elimination paradigm

Abstract: The structure of quantum theory assures the discrimination of any possible orthogonal set of states. However, the scenario becomes highly nontrivial in the limited measurement setting and leads to different classes of impossibilities, viz., indistinguishability, unmarkability, irreducibility, etc. These phenomena, often referred to as other nonlocal aspects of quantum theory, have the utmost importance in the domain of data hiding, secret sharing, etc. It, therefore, becomes a pertinent question to distill/activate such behaviors from a set, apparently devoid of these nonlocal features and free from local redundancy. While the activation of local indistinguishability in the sets of entangled states has recently been reported, other stronger notion of quantum nonlocality has yet not been inspected in the parlance of activation. Here, we explore all such stronger versions of nonlocality and affirmatively answer to activate each of them. Importantly, the possibly strongest version of such an activation is further depicted here, where none of the transformed product states can be eliminated, even if all but one of the parties come together.

Poster - 18

Maria Eduarda Reichmann Filippetto (Universidade Federal do Paraná)

An analysis on the emergence of daemonic ergotropy - quantum correlations and weak measurement

Abstract: Since the 1980s, quantum computing has been developing ever more rapidly. To optimize the use of these technologies, it is necessary not to waste resources such as work and information to the environment. In this context, it is important to understand how the thermodynamic quantities of quantum systems behave. This work aims to study the maximum extraction of thermodynamic work from quantum systems through unitary cyclic transformations [1], known as ergotropy, and its relationship with quantum correlations. Given a quantum system coupled with an ancilla, which shares quantum correlations, when a measurement is made on one of the parts of the system, information is obtained about the unmeasured part and it is then possible to generate a gain in the extraction of thermodynamic work, i.e. an ergotropy gain greater than the gain in which there are no correlations between the system and the ancilla. In the literature, quantum correlations such as quantum discord and concurrence have been calculated and related to this gain [2], but in both cases, there are states where these correlations are zero and there is still a gain. Therefore, we seek to find another quantum resource that can explain the emergence of this gain - in particular, we will initially focus on the correlation known as non-locality based on realism [3]. Also, we want to explore weak measurements and its increase in the ergotropy.

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Poster - 19

Michal Sedlák (Research Center for Quantum Information, Institute of Physics, Slovak Academy of Sciences)

Incompatibility of quantum instruments

Abstract:Incompatibility of measurements captures the fact that not all quantum measurements can be measured jointly simultaneously, and it is widely recognized as one of the most important nonclassical features of quantum theory. For example well known is the impossibility to sharply measure the position and momentum of a particle at the same time. Once the concept of incompatibility was recognized, it was first characterized through commutativity relations of sharp observables and later generalized to existence of a joint measurement device with suitable marginals to encompass the modern description of quantum measurements via the positive operator-valued measures (POVMs). However, the concept of joint measurability is an operational notion able to encompass any preparation, transformation or measurement devices. Indeed, recently the incompatibility of quantum channels, was introduced and studied. Even more recently, the concept of incompatibility was generalized by Mitra and Farkas to quantum instruments, i.e., to devices that can be used to measure the quantum system while also including the description of the post-measurement state. In particular, Mitra and Farkas proposed two possible definitions for compatibility of instruments: the traditional compatibility, which asks for finding a joint instrument with proper classical marginals, and the parallel compatibility, which captures the idea that the joint device should be able to produce all the outputs at each experimental run, including the post-measurement states for all jointly measured instruments. We prefer and study parallel compatibility of instruments due to its operational interpretation and clear reductions to known incompatibility notions in special cases. Quantum instrument reduces to a quantum channel or a POVM, if the outcome set and the output space are suitably chosen. This allows us to consider compatibility of a POVM with other POVM/channel/instrument, or compatibility of a channel with other channel/ instrument as a special case of compatibility of two instruments. We analyze consequences of instrument compatibility for the induced POVMs and channels of the two instruments. We find that compatibility with an instrument automatically implies compatibility with its induced POVM and its induced channel. Compatibility of POVMs is closely related to the concept of non-disturbance. We generalize this concept to instruments and show that if the first instrument does not disturb the second instrument several non-disturbing relations hold for their induced POVMs and channels.

Another way how compatibility problem can be approached is by studying constructions, which lead to compatible pairs. For this purpose it is natural to consider how an instrument can be postprocessed in the most general way, because application of such postprocessings will not change compatibility of a pair of instruments. Previously it was known that a pair of channels are compatible if and only if one of them can be postprocessed from the complementary channel of the other channel. We define analogous notion of a complementary instrument. One of our main results is that we were able to show that two instruments are compatible if and only if one of them can be postproccessed from the complementary instrument of the other one. Thus, we showed that verifying compatibility of a pair of instruments is equivalent to verification of the instrument postprocessing relation between one of the instruments and the complementary instrument to the other. This result can be also seen as a characterization of all instruments that are compatible with a chosen instrument. Finally, we illustrate the findings presented above by finding particular classes of compatible instruments. Especially, we characterize compatibility of pairs of measure-and-prepare instruments, and pairs of indecomposable instruments, i.e., instruments whose quantum operations are expressible by a single Kraus operator.

Poster - 20

Arjendu Pattanayak (Carleton College)

Measurement backaction control of quantum dissipation in a nonlinear oscillator

Abstract: Quantum backaction from weak measurement affects quantum dynamics. We consider quantum state evolution for a nonlinear driven quantum oscillator under continuous measurement. In one such system, the post-processing choice of phase ϕ for a local oscillator (LO) laser used in the homodyne measurement changes the form of the energy dissipation via the nonclassical spread variables. This can significantly change the energy absorbed, the size of these spread variables, and hence alter or enhance quantum effects. We discuss some examples, including where this energy in the spread variables allows for a dynamical tunneling between algorithmically complex and simple dynamics, as well as energetically separated dynamical steady-states. We sketch applications and implementation ideas

Poster - 21

Oisin Culhane (Trinity College Dublin)

The thermodynamics of the quantum Mpemba effect

Abstract: The Mpemba Effect is the paradoxical phenomenon where hot water will freeze faster than cold water; this idea has been in human knowledge since Aristotle 2000 years ago. The Mpemba effect was brought into the modern era in the 1960s by a Tanzanian secondary school student – Erasto Mpemba - while preparing ice cream. More recently, the effect has sparked interest in microscopic physics, notably in quantum systems. We investigate the quantum Mpemba effect from the perspective of non-equilibrium quantum thermodynamics by studying relaxation dynamics described by Davies maps. Starting from a state with coherences in the energy eigenbasis, we demonstrate that an exponential speedup to equilibrium will always occur if the state is transformed to a diagonal state in the energy eigenbasis, provided that the spectral gap of the generator is defined by a complex eigenvalue. When the transformed state has a higher non-equilibrium free energy, we argue using thermodynamic reasoning that this is a genuine quantum Mpemba effect. Furthermore, we show how a unitary transformation on an initial state can always be constructed to yield the effect and demonstrate our findings by studying the dynamics of both the non-equilibrium free energy and the irreversible entropy production in single and multi-qubit examples.

Poster - 22

Marco Radaelli (Trinity College Dublin)

Parameter estimation for quantum jump unraveling

Abstract: We consider the estimation of parameters encoded in the measurement record of a continuously monitored quantum system in the jump unraveling. This unraveling picture corresponds to a single-shot scenario, where information is continuously gathered. Here, it is generally difficult to assess the precision of the estimation procedure via the Fisher Information due to intricate temporal correlations and memory effects. In this paper we provide a full set of solutions to this problem. First, for multi-channel renewal processes we relate the Fisher Information to an underlying Markov chain and derive an easily computable expression for it. For non-renewal processes, we introduce a new algorithm that combines two methods: the monitoring operator method for metrology and the Gillespie algorithm which allows for efficient sampling of a stochastic form of the Fisher Information along individual quantum trajectories. We show that this stochastic Fisher Information satisfies useful properties related to estimation in the single-shot scenario. Finally, we consider the case where some information is lost in data compression/post-selection and provide tools for computing the Fisher Information in this case. All scenarios are illustrated with instructive examples from quantum optics and condensed matter.

Based on https://arxiv.org/abs/2402.06556

Poster - 23

Peter O'Donovan (Trinity College Dublin)

Quantum master equation from the eigenstate thermalisation hypothesis.

Abstract: Master equations are a ubiquitously used tool to describe systems which are coupled to an inaccessible environment. In many textbook derivations of weak coupling master equations, it is assumed that the bath is prepared in a Gibbs ensemble. This assumption is restrictive and often unjustified due to the most commonly used models in open quantum systems theory being free models, which are known to not thermalise. In this work, we consider a system weakly coupled to a chaotic bath and use the eigenstate thermalisation hypothesis to derive a Lindblad master equation. This master equation works for a much larger number of initial states, including pure states which are far from equilibrium. We numerically verify this master equation by comparing it to dynamics computed using exact diagonalization for a chaotic transverse and longitudinal field Ising model. Additionally, we compare the master equation to dynamics generated from an integrable model and show that thermalisation does not occur in this case. We believe this framework can be useful in understanding nonequilibrium phenomena in condensed matter systems with short-ranged interactions such as in quantum impurity problems. We also expect this master equation description to hold for many types of bath dynamics including Floquet models and when the system is coupled to multiple baths.