QI 39: Quantum Foundations

Time: Friday 11:00–13:00 Location: HS VIII

QI 39.1 Fri 11:00 HS VIII

Discovering Local Hidden-Variable Models for Arbitrary Multipartite Entangled States and Arbitrary Measurements — •Nick von Selzam[1] and Florian Marquardt[1,2] — [1]Max Planck Institute for the Science of Light, Erlangen — [2]Friedrich-Alexander-Universität Erlangen-Nürnberg

Measurement correlations in quantum systems can exhibit non-local behaviour, a fundamental aspect of quantum mechanics with applications such as device-independent quantum information processing. However, it is in general not known which states are local and which ones are not. In particular, it remains an outstanding challenge to explicitly construct local hidden-variable (LHV) models for arbitrary multipartite entangled states. To address this, we use gradient-descent algorithms from machine learning to find LHV models which reproduce the statistics of arbitrary measurements for quantum many-body states. In contrast to previous approaches, our method employs a general ansatz, enabling it to discover LHV models for all local states. Therefore, it for example provides actual estimates for the critical noise levels at which two-qubit Werner states and three-qubit GHZ and W states become local. Furthermore, we find evidence suggesting that two-spin subsystems in the ground states of translationally invariant Hamiltonians are genuinely local, while bigger subsystems are in general not. Our method now offers a quantitative tool for determining the regimes of non-locality in any given physical context, such as non-equilibrium, decoherence or disorder.

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QI 39.2 Fri 11:15 HS VIII

Generalizing the Mermin inequality to larger numbers of measurement settings — •Fynn Otto, Carlos de Gois, and Otfried Gühne — Universität Siegen, Germany

Multipartite Bell nonlocality is an important resource for quantum information processing. It is detected by the violation of Bell inequalities and gap between the classical bound and the quantum bound grows exponentially with the number of parties for the Mermin inequality. This inequality is limited to two measurement settings per party. Nevertheless, advantages arise by increasing the number of settings. We present a new class of symmetric Bell inequalities generalizing the Mermin inequality to an arbitrary number of measurement settings. They are maximally violated by the Greenberger-Horne-Zeilinger (GHZ) state and provide a significantly higher noise robustness. We investigate improvements in the required detection efficiency for loophole-free Bell tests and advantages for self-testing the GHZ state. Our results decrease current experimental requirements, e.g. for secure quantum communication and state verification.

QI 39.3 Fri 11:30 HS VIII

Nature cannot be described by any causal theory with a finite number of measurements — •Lucas Tendick — Inria Paris-Saclay, Bâtiment Alan Turing, FRA, 91120 Palaiseau

We show, for any $n \geq 2$, that there exists quantum correlations obtained from performing n dichotomic quantum measurements in a bipartite Bell scenario, which cannot be reproduced by $n-1$ measurements in any causal theory. That is, it requires any no-signaling theory an unbounded number of measurements to reproduce the predictions of quantum theory. We prove our results by showing that there exists Bell inequalities that have to be obeyed by any no-signaling theory involving only $n-1$ measurements and show explicitly how these can be violated in quantum theory. Finally, we discuss the relation of our work to previous works ruling out alternatives to quantum theory with some kind of bounded degree of freedom and consider the experimental verifiability of our results.

QI 39.4 Fri 11:45 HS VIII

Causal structure of quantum black-boxes — •Leonardo Silva Vieira Santos — Universität Siegen

The relationship between causality and quantum measurements is central to many of the foundational challenges in quantum theory. Key examples of this tension include Bell's theorem, the concept of "impossible measurements" in quantum field theory, and the "multi-agent paradoxes," such as Wigner's friend and its generalizations. In this work, we systematically explore how causality constrains the implementation of quantum operations and the insights it offers. We introduce a framework for causal modeling in quantum operations, deriving a range of results, including the connection between commutation and factorization (Tsirelson's problem) and information causality.

QI 39.5 Fri 12:00 HS VIII

Multi-Path and Multi-Particle Tests of Complex versus Hyper-Complex Quantum Theory — Ece Ipek Saruhan[1,2], Joachim von Zanthier[2], and •Marc-Oliver Pleinert[2] — [1]Institute for Quantum Optics and Quantum Information (IQOQI) Vienna, Boltzmanngasse 3, A-1090 Vienna — [2]Quantum Optics and Quantum Information Group, Friedrich-Alexander-Universität Erlangen-Nürnberg, Staudtstr. 1, 91058 Erlangen, Germany

The axioms of quantum mechanics provide limited information regarding the structure of the Hilbert space, such as the underlying number system. The latter is generally regarded as complex, but generalizations of complex numbers, so-called hyper-complex numbers, cannot be ruled out in theory. Therefore, specialized experiments to test for hyper-complex quantum mechanics are needed. To date, experimental tests are limited to single-particle interference exploiting a closed phase relation in a three-path interferometer called the Peres test. The latter distinguishes complex quantum mechanics from quaternionic quantum mechanics. Here, we propose a general matrix formalism putting the Peres test on a solid mathematical ground. On this basis, we introduce multi-path and multi-particle interference tests, which provide a direct probe for any dimension of the number system of quantum mechanics.

QI 39.6 Fri 12:15 HS VIII

Witnesses for non-projectively simulable POVMs — •Raphael Brinster, Nikolai Wyderka, Hermann Kampermann, and Dagmar Bruss — Institut für Theoretische Physik III, Heinrich-Heine-Universität Düsseldorf

Quantum measurements are an indispensable tool in quantum information tasks like quantum computing and quantum cryptography. Usually, one distinguishes between projective measurements and generalised measurements (POVMs), where the latter perform better in certain tasks like unambiguous state discrimination. POVMs, that can be simulated by projective measurements acting on the same Hilbert space are called projectively simulable POVMs. In general, determining whether a given POVM is projectively simulable or not is a hard problem. Analogously to entanglement witnesses, we construct non-simulability witnesses from a hierarchy of semidefinite programs. These witnesses are linear maps, which can be evaluated using measurement statistics. A negative outcome certifies non-simulability. Using this tool we calculate upper bounds on the minimum amount of white noise one has to add to make every POVM in d dimensions simulable.

QI 39.7 Fri 12:30 HS VIII

Correlations and quantum circuits with dynamical causal order — •Raphaël Mothe[1,2,3], Alastair Abbott[3], and Cyril Branciard[1] — [1]Institut Néel, CNRS, Grenoble, France — [2]University of Siegen, Siegen, Germany — [3]Inria, Grenoble, France

Requiring that the causal structure between different parties is well-defined imposes constraints on the correlations they can establish, which define so-called causal correlations. Some of these are known to be dynamical in that their causal structure is not fixed a priori but is instead established on the fly, with for instance the causal order between future parties depending on some choice of parties in the past. Here we identify a new way that the causal order between the parties can be dynamical: with at least four parties, there can be some dynamical order, which can nevertheless not be influenced by the choice of past parties. This leads us to introduce an intermediate class of correlations with what we call non-influenceable causal order, in between the set of non-dynamical correlations and the set of general causal correlations. We then define analogous classes of processes, considering the recently introduced classes of quantum circuits with classical or quantum control of causal order the latter being the largest class within the process matrix formalism known to have a clear interpretation in terms of coherent superpositions of causal orders. This allows us to formalise precisely in which sense certain quantum processes can have both indefinite and dynamical causal orders.

QI 39.8 Fri 12:45 HS VIII

Quantum-error-correction assisted test of quantum aspects of gravity — •Yixuan Wang, Julen Simon Pedernales, and Martin Bodo Plenio — Institut für Theoretische Physik, Universität Ulm, Ulm, Germany

The detection of gravitationally induced entanglement (GIE) offers a promising avenue to experimentally test those hybrid quantum-classical models of gravity that can be represented as non-LOCC (local operations and classical communication) maps. However, practical observation of such entanglement may be hindered by environmental decoherence or fundamental decoherence mechanisms, such as those postulated in wavefunction collapse models. To address these challenges, quantum error correction can play a pivotal role. In my talk, I demonstrate that local quantum error-correcting codes without introducing external entanglement enable the observation of entanglement in models of linearized gravitational interactions, even under the influence of collapse noise from models like Ghirardi-Rimini-Weber (GRW), Continuous Spontaneous Localization (CSL), or the Anastopoulos-Hu gravitational decoherence framework. Furthermore, the recovery of entanglement using local operations provides direct evidence that these combined models (linearized gravity + collapse models) deviate fundamentally from LOCC behavior.