# RQI Circuit Vienna — 10th November 2023, IQOQI Vienna

## Abstracts

### Časlav Brukner

Quantum reference frames, indefinite causal order, Wigner and his friends

Our group's research is based on the premise that physical phenomena must ultimately be described in terms of operationally well-defined concepts. We apply operational and information-theoretic tools to a range of questions: Can causal relations be indefinite in a quantum mechanical sense? How does physics "look like" from the perspective of a quantum particle? Is the nature of reality ultimately relational? I will give an overview of the state of knowledge on these topics.

### Luca Apadula

Quantum Reference Frames for Lorentz Symmetry

Since their first introduction, Quantum Reference Frame (QRF) transformations have been extensively dis- cussed, generalising the covariance of physical laws to the quantum domain. Despite important progress, a formulation of QRF transformations for Lorentz symmetry is still lacking. The present work aims to fill this gap. We first introduce a reformulation of relativistic quantum mechanics independent of any notion of preferred temporal slicing. Based on this, we define transformations that switch between the perspectives of different relativistic QRFs. We introduce a notion of "quantum Lorentz transformations" and "superposition of Lorentz boosts", acting on the external degrees of freedom of a quantum particle. We analyse two effects, superposition of time dilations and superposition of length contractions, that arise only if the reference frames exhibit both relativistic and quantum-mechanical features. Finally, we discuss how the effects could be observed by measuring the wave-packet extensions from relativistic QRFs.

### Veronika Baumann

Different perspectives in (non)-causal quantum processes

The process matrix framework was developed to allow for scenarios with indefinite or quantum causal order, a phenomenon that is expected to be relevant for quantum gravity. A popular approach towards a quantum theory of gravity is the Page-Wootters formalism, which describes time-evolution of systems via correlations between a clock system and other quantum systems encoded in history states. We combined the process matrix framework with a generalization of the Page-Wootters formalism with multiple clocks. Each of these clocks can be thought of as corresponding to an agent and conditioning on a certain clock gives the respective agent's perspective inside an a priori general quantum process. We implemented scenarios where different definite causal orders are coherently controlled and explain why certain non-causal processes might not be compatible within this framework.

### Eleftherios-Ermis Tselentis

The Möbius game and other Bell tests for relativity

We derive multiparty games that, if the winning chance exceeds a certain limit, prove the incompatibility of the parties' causal relations with any partial order. This, in turn, means that the parties exert a back-action on the causal relations; the causal relations are dynamical. The games turn out to be representable by directed graphs, for instance by an orientation of the Möbius ladder. We discuss these games as device-independent tests of spacetime's dynamical nature in general relativity. To do so, we design a relativistic setting where, in the Minkowski spacetime, the winning chance is bound to the limits. In contrast, we find otherwise tame processes with classical control of causal order that win the games deterministically. These suggest a violation of the bounds in gravitational implementations. We obtain these games by uncovering a "pairwise central symmetry" of the correlations in question and by reducing the problem to the acyclic subgraph problem, a known NP-complete linear combinatorial optimization problem. In addition, we derive multiparty games in a scenario where the polytope dimension grows only linearly in the number of parties. Here, exceeding the limits not only proves the dynamical nature of the causal relations, but also that the correlations are incompatible with any global causal order.

**Markus Müller**

How spacetime symmetries and the structure of quantum theory constrain each other

In the talk, I will describe two complementary but related research directions of our group: 1) the conceptual and mathematically rigorous treatment of quantum reference frames; and 2) insights into how spacetime and quantum physics mutually constrain each other. Topic 2 utilizes quantum foundations techniques like generalized probabilistic theories and the (semi-)device-independent approach, and it turns out that these tools enable us to obtain fascinating insights into the relation between space, time and probabilities. As examples, I will present a recent paper establishing a one-to-one correspondence between the amount of entanglement in the Page-Wootters mechanism and the amount of time-translation asymmetry that the imperfect clock generates (Phys. Rev. Lett. 129, 260402, 2022), and an earlier result relating the three-dimensionality of the qubit Bloch ball to relativity of simultaneity (Proc. R. Soc. A 473, 20170596, 2017). After this talk, Stefan Ludescher will present a result on "spacetime boxes", namely a semi-device-independent randomness generation scheme whose security relies only on spatial symmetries and not on the validity of quantum theory (arXiv:2210.14811).

**Stefan Ludescher**

Theory-independent randomness generation with spacetime symmetries

We introduce a class of semi-device-independent protocols based on the breaking of spacetime symmetries. In particular, we characterise how the response of physical systems to spatial rotations constrains the probabilities of events that may be observed: in our setup, the set of quantum correlations arises from rotational symmetry without assuming quantum physics. On a practical level, our results allow for the generation of secure random numbers without trusting the devices or assuming quantum theory. On a fundamental level, we open a theory-agnostic framework for probing the interplay between probabilities of events (as prevalent in quantum mechanics) and the properties of spacetime (as prevalent in relativity).

**Markus Aspelmeyer**

Title: TBA

Abstract: TBA

**Marios Christodoulou**

Table Top Quantum Gravity: Some perspectives for the future

The topic of Table Top Quantum Gravity has occupied a large space in the scientific literature the past 5 years both on theory, experiment and philosophy/epistemology. I will give a quick overview of a selection of main developments in TTQG as well as some tangential research avenues partly inspired by and entangled with this topic.

**Thomas Galley**

Principle based approaches to the study of the quantum nature of the gravitational field

In this talk I will outline the difference between a 'principles' approach to physics as opposed to a 'model based' approach. I will show how one can apply the principle based approach to the current discussions around table top tests of the quantum nature of the gravitational field, by using the framework of general probabilistic theories. Finally I will argue that principle based approaches are especially relevant to interdisciplinary research areas such as this one, and outline some open research questions.

**Andrea Di Biagio**

When does relativistic locality imply subsystem locality?

Relativity and quantum information use different notions of locality. In relativity, locality is tied to spacetime regions while, in QI, locality is based on the notion of subsystems. What is the relation between these notions? In this talk we will investigate this question for a simple quantum field theory model and see how relativistic causality implies subsystem locality---approximately. We will then comment on whether we can expect this result to generalise to more realistic QFTs, and how it relates to no-go theorems about low-energy quantum gravity.

**Maria Papageorgiou**

Aspects of QFT measurements

The development of a consistent and practicable local measurement theory for QFT is an exciting ongoing project that is currently being pursued by many different communities, from quantum information and mathematical physics to history and philosophy of QFT. Considerations of relativistic causality have played an important role in these developments. For example, as I will discuss, general morals can be drawn from the variety of recent responses to the "impossible measurements" problem, first raised by Sorkin. Then, I will focus on detector models in QFT, which can be viewed as useful tools for modeling local QFT measurements. In this context, I will mention work that is motivated by the following questions: are the signaling relations between detectors compatible with the spacetime notions of relativistic causality? which field observables are being recorded by certain detector models? Finally, I will discuss the advantages of solvable models (that work beyond perturbation theory) in interpreting the detector's response in the weak and strong coupling regime, as well as possible frictions with relativistic causality.

**Luis C. Barbado**

Unruh effect and Hawking radiation for detectors in quantum superposition of trajectories

Unruh effect and Hawking radiation are two of the most important predictions of Quantum Field Theory in curved space. As it is well known, these thermal radiations are perceived differently by different observers in a given spacetime. Such dependence can be analyzed by considering the excitation of a quantum particle detector coupled to the radiation field and following different trajectories. We present recent works in which we extend this sort of analysis to the case in which the detectors do not follow definite trajectories, but rather quantum superpositions thereof. More concretely, we consider a multilevel particle detector coupled to a massless real scalar field, and following a superposition of accelerated trajectories in a given Rindler wedge (for the Unruh effect), or of static trajectories outside a Schwarzschild black hole (for Hawking radiation). We find that, after the interaction with the field, the state of the detector is not in general a classical mixture of the excitations expected for each of the trajectories in superposition separately, but rather some coherences survive. These coherences are a result of the non-distinguishability of the different possible states in which the radiation field is left. Their dependence on the different excited energy levels and the different superposed trajectories can be associated physically to the characteristics of the absorbed particle of the field. The results are briefly discussed in the context of Quantum Reference Frames, and future extensions are considered.