NÉEL INSTITUTE Grenoble

PhD thesis project

Indefinite causal structures in fermionic systems and beyond quantum theory

Context: Quantum mechanics has allowed communication and information processing to go beyond previously set classical limits, by exploiting "quantum resources" which are strictly non-classical phenomena, like entanglement and superposition. Another resource discovered recently is the new type of causality relations in quantum processes. It has been shown that quantum mechanics allows systems to exist in a superposition of states with different causal orderings of quantum operations (processes). Such states have no well-defined causal ordering and are thus purely non-classical. It was also shown that such indefinite causal structures can have advantages in quantum communication so that causality can indeed be considered a resource here.

A theoretical framework commonly used to study indefinite causal orders is the "process matrix formalism", which involves the construction of a process matrix associated with the system that encodes the causal resource between the local observers. While all physical processes have a corresponding process matrix which can be derived regardless of whether the causal order is well- defined, the reverse is not so straightforward – i.e., it is in general unclear whether a given process matrix corresponds to a physical process. Not only that, but it is also not defined what subset of process matrices can actually be observed physically. The non-classical nature of indefinite causal orders can in certain cases give rise to the violation of causal inequalities, similar to how entanglement can lead to the violation of Bell's inequalities – although whether any physical process can lead to such violations, and whether these can actually be observed experimentally, remain open, highly debated questions in the field.

Objectives: As just seen, the link between the process matrix formalism and physical realizations of quantum processes is unclear. It is also not fully clear what the role of superposition and entanglement is in the causal indefiniteness of process matrices.

To try and clarify these, we propose in this project to investigate causal indefiniteness in more general contexts than those studied so far. For that, we will take Fermionic systems as a starting point to extend our investigations, as Bosonic systems do not show anti-commutation relations or superselection. Also, the study of fermionic systems can potentially be extended to parafermions, Majorana fermions, and even anyons. We will then further extend to more general theories, beyond quantum theory, using the framework of generalized probabilistic theories (GPTs), with the goal of understanding causality as a quantum resource as well as the relation between causal indefiniteness and other non-classical resources.

Interdisciplinary aspects: The project falls under the realm of quantum information theory. The outcomes of the project, however, have potential applications mainly in the development of quantum technologies and quantum communication. Furthermore, the results of the project give us some insight into causality, which plays a very important role in logic and computation, as well as causal inference in quantum machine learning. Finally, the study of foundations of physics such as quantum gravity will also benefit from this project.

Possible collaboration and networking : This internship fits in part with a new ANR project obtained in collaboration with A. Abbott at INRIA Grenoble, Alexei Grinbaum at CEA Saclay and Pablo Arrighi at University of Saclay, which will provide opportunities for collaborations. The student will also work in close contact to the other theory students in our group.

Required skills: Deep knowledge of the formalism of quantum theory, and acquaintance with the field of quantum information, more specifically; interest in the foundations of (quantum) physics.

Starting date : 1st semester 2023

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