Centre for Quantum Information and Communication
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Mémoires de Fin d'Etudes pour l'année académique 2020-21

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Thème général : Sciences de l'Information Quantique

Etudiants concernés : Ir. Physique ou Ms. Science Physique
Ir. Informatique ou Ms. Science Informatique

Pré-requis : Tous les sujets nécessitent des connaissances de base de mécanique quantique, de théorie des probabilités et d'algèbre linéaire.

Note : Certains sujets sont plus proches de la physique quantique (optique quantique, communication quantique, thermodynamique quantique), d'autres de l'informatique quantique (algorithmes quantiques, complexité quantique) ou d'autres encore concernent les fondements de la physique quantique.

Langue : Français ou anglais en fonction de la personne qui supervise le mémoire (par souci d'uniformité, tous les sujets sont présentés en anglais ci-dessous)

1) Continuous majorization relations in quantum phase space

Supervisor : Nicolas Cerf, co-supervisor : Zacharie Van Herstraeten

The theory of majorization provides a way of comparing probability distributions in terms of disorder. The condition that P majorizes Q means that P is more ordered than Q, in the sense that applying a well-chosen random permutation to P yields Q (consequently, P has a lower entropy than Q). While it is a powerful tool in statistics, economy, and various fields based on probabilities, majorization theory also turns out to have many applications in quantum information sciences, for example in relation with quantum entanglement or quantum channel capacity. This Ms thesis will investigate a much less explored *continuous-variable* counterpart of majorization theory and analyse its potential application in quantum physics. In particular, the focos of the project will be the role of majorization for comparing Wigner distributions in quantum phase space (*x,p*). We have good reasons to anticipate that it gives a way to address a conjectured (but still pending) entropic uncertainty relations for position and momentum variables (namely, the fact that the vacuum state continuously majorizes all quantum states with a positive Wigner function). In a second time, the objective of the Ms thesis will be to explore the possibility of extending the use of continuous-variable majorization relations to quantum states with non-positive Wigner functions (the Wigner function is a quasi-probability distribution, which is normalized as a genuine probability distribution but may admit negative regions in phase-space).

2) Photonic interference in linear optical circuits

Supervisor: Nicolas Cerf, co-supervisor : Leonardo Novo

Photonic quantum interference is a key resource for implementing future quantum technologies with photonic integrated devices, and in particular for so-called « boson sampling » devices. For this reason, there has recently been a strong interest in genuine multiphoton multimode quantum interference effects, going beyond the celebrated Hong-Ou-Mandel effect (an interferometric suppression effect that is due to the quantum indistinguishability of two photons : the trajectory where they are both reflected at a 50:50 beam splitter interferes destructively with the trajectory where they both cross the beam splitter). In interferometers with certain symmetries, multiphoton quantum interference effectively suppresses certain sets of detection events, which, mathematically, can be related to properties of the permanent of a matrix describing the interferometer. (NB : The permanent of a matrix is similar to its determinant but with all negative terms being turned into positive terms. It appears here because we deal with photons, hence bosons.) In this Ms thesis, we intend to identify such suppression effects in Fourier interferometers, which can be viewed as a multimode version of a 50:50 beam splitter. This is already well understood for an even number of modes, but the case of an odd number of modes is still unresolved. In a second time, the objective is to explore the possible extremality of Fourier interferometers among a class of multiport linear interferometers. Mathematically, this would boil down to give the statement and attempt to prove the quantum counterpart of a central theorem on the permanent of doubly-stochastic matrices. A third possible line of research would be to build on the set of recurrence equations describing multimode interferences that have recently been found at QuIC. As these equations combine the permanents and determinants of specific matrices, the objective would be to provide a physical model combining bosonic and fermionic quantum interferences.

3) Resource theory in quantum thermodynamics

Supervisor: Nicolas Cerf, co-supervisors : Uttam Singh & Siddhartha Das

Thermodynamics is a macroscopic theory applicable in the limit where the number of particles and volume tend to infinity. However, with our increasing ability to control and manipulate small systems, such as the realization of molecular motors and nanomachines, the scope of applicability of thermodynamics is starting to stretch beyond the macroscopic region. One of the main goals of the thermodynamics of small systems – a new field called quantum thermodynamics – is the extraction of work by means of cyclic Hamiltonian transformations of a quantum state. Quantum thermodynamics can be cast as a « resource theory » by viewing the Gibbs state (thermal state) as a state that is « free » and hence any other state as a resource for work extraction. In quantum thermodynamics, the notion of a (quantum) passive state generalizes the notion of thermal states of thermodynamics: it is a state from which no work can be extracted by means of any unitary operator applied to the quantum system. The objective of this Ms thesis is to pursue a recent research project at QuIC, where the non-passivity of a state (the ability to extract work from it) is treated as a « resource ». A resource theory of non-passivity and so-called resource « monotones » could be built based on this idea. Alternatively, other sets of free states could be explored in this context, such as states with a thermodynamically relevant symmetry (e.g., states that are invariant under any energy-preserving unitary). For example, the study could possibly be restricted to bosonic systems (a set of harmonic oscillators or optical modes) and take as « free » the states that are invariant under the action of any linear optical circuit. Another direction of the Ms thesis concerns a new majoration relation, found at QuIC, which leads to a quantitive way of comparing two passive states (just as two thermal states can be compared in terms of their temperature – one is colder than the other). The objective is to find interesting applications of this notion.

4) Adiabatic quantum computing via Markovian dynamics

Supervisors: Jérémie Roland & Ognyan Oreshkov & Nicolas Cerf

Quantum computers promise to solve certain problems more efficiently than classical computers. The standard model of quantum computation works by applying a sequence of quantum gates (or unitary operations) on a set of qubits. An alternative model, which is equivalent in computational power, is Adiabatic Quantum Computing. In this model, the quantum computer is initially prepared in the ground state of a specific Hamiltonian, and the computation works by slowly turning off this Hamiltonian while at the same time turning on another one whose ground state encodes the solution of the computational problem. If this interpolation is performed slowly enough, the quantum adiabatic theorem guarantees that the initial ground state will be transformed into the final ground state.

Recently, the adiabatic theorem was extended from the case of closed quantum system undergoing Hamiltonian dynamics to the case of open quantum systems undergoing dissipative Markovian dynamics, and it was shown that this more general type of adiabatic dynamics can be used to perform various tasks. This project will explore the possibility to perform adiabatic quantum computation via adiabatic Markovian dynamics.

5) Applications of the quantum linear systems algorithm
Supervisor: Jérémie Roland

Algorithms to solve linear systems find applications in a wide range of fields. Quantum algorithms for solving linear systems outperform its classical counterpart and in some regimes, fare exponentially better. This project would aim at exploring the applications of this quantum algorithm to various problems and also at techniques that help in extracting useful information from its output. This would also involve analyzing existing techniques by which quantum computers can simulate quantum systems faster than any classical computer. Successful completion of this project will lead to improving existing quantum algorithms for data-fitting and to better quantum algorithms for estimating the time required by a quantum walker to hit a given set of vertices in a graph.

6) Quantum processes with indefinite causal order on time-delocalised subsystems
Supervisor: Ognyan Oreshkov, co-supervisor : Julian Wechs

In recent years, the investigation of causal relations in quantum theory has attracted a lot of interest. In particular, it has been found that there exist higher-order quantum processes (that is, transformations that themselves act on quantum operations) which are not compatible with a definite causal order. A central – though pending – question in this context is which of these higher-order processes have a practical realisation, and in what physical situations they can occur. It has been found that some processes with indefinite causal order can be realised on so-called time-delocalised subsystems, that is, by applying the operations on quantum subsystems that are not associated with a definite time.

The aim of this master project is to identify and study new examples of quantum processes with indefinite causal order on time-delocalised subsystems.

7) New symmetry transformations through post-selection
Supervisor: Ognyan Oreshkov

The concept of symmetry is fundamental for our understanding of the laws of physics. It was recently shown that reconciling the probabilistic laws of quantum theory with the requirement for time-reversal symmetry requires a generalized formulation of quantum theory, which implies the possibility for more general symmetry transformations than those previously believed possible. This Ms thesis will explore the possibility of realizing this new type of symmetry transformations through post-selection.

8) Quantum Causal Models vis-à-vis Quantum Measure Theory: their interplay in Bell scenarios
Supervisor: Ognyan Oreshkov, co-supervisor : Ravi Kunjwal

This project will focus on issues of causality in quantum theory and beyond. Broadly, we aim to use the framework of Quantum Causal Models (QCM) – an agent-centric approach to model causality – to understand aspects of Sorkin's Quantum Measure Theory, an approach to quantum-like theories that seeks realist underpinnings for quantum theory in terms of histories. The latter is motivated by a path-integral (or sum-over-histories) approach to quantum gravity, namely, causal set quantum gravity. We will focus on the relation between these two frameworks in the case of Bell scenarios, where the existence of a strongly positive joint quantum measure (SPJQM) puts strong constraints on quantum Bell violations (cf. Dowker et al.). Dowker et al. were motivated by a search for 'quantum Bell causality', an appropriate generalization of local causality in Bell scenarios. Like local causality, quantum Bell causality would implement an *ontological* notion of relativistic causality that preserves no-signalling (an *operational* consequence of relativistic causality), but unlike local causality, quantum Bell causality would allow for violations of Bell inequalities. Just as requiring local causality is equivalent to requiring the existence of a joint probability distribution constraining classical correlations in Bell scenarios, they hoped that an appropriate notion of quantum Bell causality would be equivalent to the existence of a SPJQM. The framework of QCMs, on the other hand, comes with the quantum Markov condition, which -- at first glance -- seems to provide a candidate for a 'quantum Bell causality' condition in the sense that it generalizes the classical Markov condition, the analog of local causality. We will explore whether this qualitative insight can be turned into a quantitative result, perhaps reformulating the condition of SPJQM in terms of a constraint on process operators, and/or conversely. The consequences of this for realist underpinnings of quantum causal models (QCMs) will also be explored. This project could also provide insight into the challenge of formulating an `almost quantum theory' that realizes the 'almost quantum' set of correlations in Bell scenarios (cf. Boes and Navascues). Another worthwhile direction, moving away from Bell scenarios, is to explore the connection between the lack of third-order interference and contextuality in quantum theory (cf. Henson).

9) Contextuality in quantum physics
Supervisor: Ognyan Oreshkov, co-supervisor : Ravi Kunjwal

The notion of contextuality in quantum theory arose from foundational considerations starting in the 1960s and, in its modern form, multiple incarnations of this notion have appeared in the quantum foundations and quantum information litterature. In this project, we will adopt a noise-robust notion of contextuality, first proposed by Spekkens. The goal of this project will be to look for the role that contextuality plays in quantum physics, broadly understood: in particular, what are the physical phenomena in which contextuality naturally arises and how might one witness it in an experiment? We aim at developing applications of contextuality where its witness is native to the phenomenon of interest and quantitatively useful. Some potential directions include (but are not limited to):

- Contextuality in quantum computation with magic states,
- Contextuality in quantum thermodynamics,
- Contextuality vis-à-vis anomalous weak values,
- Applications of hypergraph frameworks for noise-robust contextuality to quantum information, and
- Foundational role of contextuality vis-a-vis interpretational issues in quantum theory.

The specific course of the project will depend on the individual interest(s) of the student(s).