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*Quantum Causality and the Indefinite Thermodynamic Arrow of Time*

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Abstract:

To date, all quantum mechanical experiments that have been performed agree with the assumption that quantum mechanical laws can be applied to any conceivable system. The working hypothesis of this thesis is that these laws can be extended to the notion of time, and, consequently, to the way in which two or more events can causally influence one another. This would have far-reaching consequences as our entire understanding of the world is based on the study of the causal relations between physical phenomena. The aim of this thesis was, hence, to investigate the consequences of the application of quantum mechanics to the causal relations among events and to the thermodynamic arrow of time.

The first part of this thesis concerns three studies falling under the umbrella of ‘indefinite causality’, i.e., the notion according to which the causal structure between events may become genuinely indefinite. Such a scenario is expected to arise naturally in regimes wherein quantum mechanics and general relativity are both relevant and where the metric and, consequently, the causal structure may “fluctuate”. In quantum optical experiments, indefinite causal structures can be realized by superposing the trajectories along which two events are occurring in alternative orders. Along this line, the first work of this thesis constitutes the first experimental demonstration of the indefinite causality of a process through the measurement of a ‘causal witness’,i.e., a mathematical object designed to produce a certain outcome whenever a process is not consistent with a well-defined causal order. Following up on this first study, the second work of this thesis experimentally demonstrates indefinite causality outside the quantum formalism. This is achieved by showing the incompatibility of the experimental results with a class of generalised probabilistic theories complying with the assumptions of locality and definite temporal orders. The third work of this thesis looks beyond the concept of indefinite causality, to cover a variety of quantum superpositions of trajectories. Trajectories can be used as quantum control to regulate the order of different noisy communication channels, but this is not the only configuration in which the channels can be arranged. This third work, hence, experimentally compares different ways in which two trajectories can be superposed through a pair of noisy channels, demonstrating that this artifice allows for the transmission of quantum information even when standard quantum communication protocols (where a system travels along a well-defined trajectory) fail.

The second part of this thesis comprises two studies pertaining to the field of quantum thermodynamics. The linking element between the previous part of this thesis and the present one is rooted in the concept of thermodynamic arrow of time and its directionality. In fact, the second law of thermodynamics allows one to associate a positive (negative) entropy variation in a thermodynamic process with the temporal “forward” (“time-reversal”) direction. The fourth work of this thesis, thus, proposes that quantum mechanics may permit quantum superpositions between thermodynamic processes yielding two opposite entropy variations. This would enable the existence of processes with a genuinely indefinite time’s arrow. In more detail, this work focuses on understanding whether such superpositions entail any observable consequences, and how a well-defined temporal axis emerges upon performing suitable measurements of entropy production. In this regard, this work shows that when very large quantities (in module) are observed in a measurement of the entropy production, this yields the effective projection of the quantum superposition of thermodynamic time’s arrows onto a well-defined temporal direction. On the other hand, when small quantities of entropy

production are at stake, interference effects play a prominent role in the definition of the nature of the thermodynamic process. For instance, they can lead to the observation of work probability distributions of a process that may be more or less reversible than the individual ones composing the superposition, or any classical mixture thereof. All these results revolve around the application of so-called ‘thermodynamic fluctuation theorems’. Thermodynamic fluctuations relate the difference in free energy between two equilibrium states with the work performed on a system driven far from equilibrium. Since the definition of work in quantum contexts is a non-trivial concept, the last study of this thesis proposes a simple interferometric scheme that, leveraging the use of fluctuation theorems, enables a direct estimate of the work distribution and of the average work dissipated during an isothermal thermodynamic process.

The investigation of indefinite causal structures and of the arrow of time may enable novel quantum information and quantum thermodynamic tasks, and provide methodological tools for future quantum theories of gravity. To this end, proposing and implementing experimental approaches towards these goals, as undertaken in this thesis, may help to lay the groundwork for a deeper understanding of the concept of time and its role in major physical theories. In my view, this may be where future conceptual turning points will originate from.