Abstract

Apart from an initial spark in the early 1990's, the idea of superposing the time evolution of quantum systems was put aside. Many years later, in the quest of formulating a successful theory of quantum gravity, the concept of indefinite causal order (ICO) was developed, which itself contains superposition of time evolutions. Physically, ICO would be the result of having uncertainty in the spacetime metric itself, inserting quantum uncertainty into the core of general relativity. The ICO concept can be operationally incorporated in the so-called process matrix formalism, which is a generalization of the density matrix acting on two or more quantum channels, returning some probability distribution over different measurement results. It happens that process matrices that cannot be decomposed as convex combinations of causally-ordered terms, whose technical denomination is causal non-separability, are said to contain ICO. Moreover, there are process matrices containing ICO that violate what are called causal inequalities (CIs), analogous to Bell inequalities, and those that do not violate them. The former has to this day only an abstract description and no exact physical mechanism originating it has been completely thought through. Largely due to it, it is not known if they are in fact physical. The latter can be collectively called controlled-superposition of causal orders (cSCO), whose main implementation is known as the quantum switch (QS). This process has been already implemented in the laboratory by different research groups and has been suggested to offer advantages in areas such as quantum computation, quantum communications, quantum metrology and quantum thermodynamics. Within the two categories of ICO processes, this thesis puts forward studying them in the context of thermodynamics. For those process matrices violating CIs, we focus on finding out whether thermodynamics through its second law constrains their existence. By combining different models from the literature, we develop a framework in which the second law of thermodynamics (SLT) is never violated by any bipartite process matrix with two-dimensional systems. Considering the universality of the SLT, this is an indicative that these ICO processes are indeed physical. Our results agree with previous research output where ICO processes were shown to not allow extra work extraction when compared to causally-ordered strategies. Nevertheless, the result is not conclusive and further studies must be done. On the other hand, for the processes that do not violate CIs, specially the QS, we present technical results of applying it to activate passive states and the instabilities of the QS for a control degree-of-freedom that interacts with a thermal environment. Both have considerable impact for including thermal effects in the description of technological implementations of the QS. We consider that this thesis adds valuable knowledge to the growing efforts of understanding ICO and harnessing it for real life applications.

Keywords: Indefinite Causal Order; Thermodynamics; Causal Inequalities; Quantum Switch; Quantum Information Theory.