2版

様　式　C－19、F－19－1、Z－19　（共通）

科学研究費助成事業　　研究成果報告書

令和　元 年　 6 月 24 日現在

機関番号：１３９０１
研究種目：若手研究(B)
研究期間：2017～2018
課題番号：１７K１７７９６

研究課題名（和文）量子論の時間的相関関係の研究

研究課題名（英文）Study of time-like correlations in quantum theory

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交付決定額（研究期間全体）：（直接経費）　　2,200,000円

研究成果の概要（和文）：量子系は古典系よりもはるかに強い相関を持つ。その一例である量子もつれは、互いに異なる位置にある複数の量子系の間に生じる空間的な相関であり、量子情報科学の根幹をなす重要な概念である。一方、同一の量子系の間の時間相関に関する研究は、あるデバイスが量子的に振る舞うか古典的に振る舞うかの判別で非常に重要であるにもかかわらず、あまり研究されていない。

本研究の主結果は、空間的、および時間的量子相関を統一的に研究するための枠組みを構築することであった。本研究では、量子プロセッサを実験的に検証、評価する方法を提案した。この方法は、実験に用いるデバイスに制御不能なノイズがある場合であっても有効である。

研究成果の学術的意義や社会的意義
The academic significance of this research has been to initiate a systematic study of quantum correlations in time, producing experimentally implementable tests to benchmark both presently available as well as future quantum technologies, against classical simulations without any quantum advantage.

研究成果の概要（英文）：It is now well-known that quantum systems can exhibit correlations that are much stronger than classical ones. An example is provided by quantum entanglement, lying at the core of quantum cryptography and quantum computation. However, quantum entanglement can only exist between quantum systems placed at different locations in space. The natural question then arises: what sort of correlations does quantum theory allow for the same system considered at different instants in time? Not much is known about such "quantum correlations in time," even though they also play a crucial role in discriminating quantum devices from classical ones.

The main result of this project has been the formulation of a framework able to describe, for the first time, both quantum correlations in space and in time on an equal footing. This has led to the proposal of experimentally feasible tests to verify and benchmark quantum processors, also in the presence of uncontrollable noise in the experimental devices.

研究分野：量子情報科学

キーワード：量子情報　量子もつれ　量子熱力学

１．研究開始当初の背景

It is now well-known that quantum systems can exhibit correlations that are much stronger than classical ones. One example is provided by quantum entanglement, which is the property that allows for quantum cryptography and quantum computation, both impossible on a classical computer. For its theoretical and practical relevance, quantum entanglement has been extensively studied, and various methods to characterize, verify, and benchmark quantum entanglement have been developed in the literature.

Nonetheless, one aspect of quantum entanglement is often overlooked, namely, that quantum entanglement is defined only as a property between quantum systems placed at different locations in space: there is no standard understanding of what "quantum entanglement in time" should be. However, in many situations, including communication theory, quantum computation, and quantum thermodynamics, it is important to describe not only correlations between separated systems, but also correlations that exist between one system and itself at later times. Such correlations, sometimes called "autocorrelations," play a crucial role in discriminating quantum devices from classical ones. In particular, while in the classical theory there is no intrinsic difference between correlations in space and correlations in time, in quantum theory the formalism used to describe the two is complete different. For this reason, while a lot of research has been devoted to the study of quantum entanglement, not much is known about quantum correlations in time.

When this project started, in April 2017, one of the main open problems in quantum information science was to understand how a genuinely quantum device could be verified against a classical simulator. In other words, what was missing at the time, was a way to verify, in a faithful way, non-classical correlations in time. Some tests were available, but they would all rely on using the device to distribute quantum correlations in space, and then use known techniques to verify quantum entanglement. Such methods, however, would all require the presence of an auxiliary perfect quantum memory, to store one system, while the other is fed through the device. Moreover, such methods would be either not faithful, or too much reliant on assumptions untenable in a practical experiment. Therefore, at the time, no satisfactory methods existed to directly test the correlations established by a quantum device.

２．研究の目的

The present research project promised to fill the above mentioned gap, by explicitly formulating statistical tests to benchmark the correlations established by quantum devices, without the need of any auxiliary side resource or any unreasonable assumptions.
The principal aims of the project have been articulated in four points:

a) the mathematical formulation of quantum device benchmarking in terms of statistical games;
b) the theoretical proof that such a family of statistical games constitutes a complete set of benchmarks, that is, for each genuine quantum device there exists at least one game that is able to accept it;
c) the introduction into the framework of realistic models of noise, so to guarantee that the proposed benchmarks can be implemented with current quantum control technology;
d) the specialization of the formalism to the case of practically relevant quantum processes, in particular, quantum thermal processes.

３．研究の方法

The project moved from the method developed in [F. Buscemi, Phys. Rev. Lett., vol.108, pp.200401 (2012)] to study quantum entanglement, which has been modified in order to make it applicable also to the case of quantum correlations in time. In particular, the idea has been that of using the theory of quantum statistical comparison, developed in [F. Buscemi, Comm. Math. Phys., vol. 310, pp.625-647 (2012)], as a common formalism to characterize quantum correlations, both in space and in time, in an operational and experimentally accessible way.

The problem has been formulated in game-theoretic terms as follows. A game is played between a referee and a player (Alice). The referee gives Alice a piece of information (the question "x"), waits for some time, and then asks her another question "y". Alice then chooses her answer "a" and the payoff is computed as a function f(x,y,a). This scenario is very similar to that of random access codes, since it measures Alice's ability to store information (the first question "x") and retrieve it on demand (the second question "y"). However, since here we were interested in quantum time-like correlations, classical random access codes could not be used. We therefore considered "quantum random access codes", in which the questions "x" and "y" are encoded on quantum states.

We first run some preliminary numerical simulations, finding that Alice's expected payoff in a quantum random access code game is directly related with the strength of quantum correlations in time that Alice is able to maintain between the time at which question "x" is asked, and the (later) time at which question "y" is asked. Then, we considered the setting in an abstract mathematical formulation and proceeded with the formal proofs of the result.

In the second part of the project, we focused in particular on quantum thermodynamical processes as special cases of quantum correlations in time. In particular, we adopted the use of algebraic tools and information-theoretic tools. The algebraic approach was aimed to characterize thermodynamical processes as completely positive instruments satisfying suitable properties. The information-theoretic approach was aimed to provide necessary and sufficient conditions for the existence of a thermodynamical process in terms of information-theoretic measures like entropy and mutual information.

４．研究成果

The main results achieved have been, as promised, the following two:

a) the formulation of a complete set of benchmark tests to verify quantum correlations in time (results published in Physical Review X and Physical Review Letters);
b) the information-theoretic characterization of quantum thermal processes (result published in Nature Communications).

Concerning the first result, we were able to construct a family of statistical tests that can be run to verify whether a given device is genuinely quantum or not. This amounts to verifying whether the input/output correlations (that is to say, the correlations in time) generated by the device are truly non-classical, or could be simulated by a classical computer. We were also able to "order" quantum devices in terms of their "degree of quantumness," thus obtaining a complete benchmark for quantum memories. The tests we designed are robust against various sources of noise: they can be run, in particular, with very noisy measurement apparatus. This feature is particularly useful in practical experiments, where measurements on quantum systems are quite difficult to control.

Again about the first point, we also investigated what kind of correlations in time are allowed in quantum theory. From the theoretical side, we constructed alternative theories, resembling quantum theory, but with a very different structure for the set of allowed correlations in time. This result is mathematical, however, it helps understanding where quantum theory is special and different from other possible theories, including the classical theory. It is important when the goal is to verify that a quantum device is quantum or not.

Concerning the second point, we were able, for the first time, to characterize quantum thermal processes in terms of a set of necessary and sufficient information-theoretic conditions. Our result is mostly theoretical, however, it finally clarifies what are the resources at play in quantum thermodynamics: these are the ability of a system to work as a thermometer or as a clock. While classically there is no restriction about the simultaneous measurements of energy and time, in quantum theory there is a problem since the two quantities are incompatible. As a consequence, it is possible to argue that quantum thermodynamics is a theory that aims to describe two incompatible entities at the same time. Ultimately, this constitutes the reason why quantum thermodynamical systems can behave differently from classical ones. Our result, which answers a long standing open question in quantum information science, is formulated as a statistical comparison of quantum channels [F. Buscemi, Prob. Inf. Trans., vol. 52, 201-213 (2016)].

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〔図書〕（計　0　件）

〔産業財産権〕
○出願状況（計　0　件）

名称：
発明者：
権利者：
種類：
番号：
出願年：
国内外の別：

○取得状況（計　0　件）

名称：
発明者：
権利者：
種類：
番号：
取得年：
国内外の別：

〔その他〕
ホームページ等

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