Topical: Quantum Correlations and Foundations of Quantum Field Theory in Deep Space Experiments

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1 Executive summary

The last two decades witnessed the explosive growth of Quantum Infrormation Science (QIS), driven by our increased understanding and control of Quantum Correlations, like entanglement. Quantum correlations define powerful resources for quantum computing, quantum metrology, quantum communication and more. A huge number of experiments has explored the properties of entanglement, verified the violations of Bell inequalities [2] and pushed the limits of quantum information technologies. The extension of the latter to space has led to the current record for quantum teleportation at 1400 km [1].

Despite the explosion in the development and applications of QIS, its theoretical foundation is surprisingly lacking in a major portion. Our understanding of QIS is far lagging behind the fully developed quantum theory of nature, namely, QFT, which has proven its validity and worth in the full range of physical sciences from particle-nuclear physics to atomic, optical and condensed matter physics, from quarks to black holes and the early universe. So far, quantum information theory has been largely developed in the context of non- relativistic quantum mechanics, a small corner of full QFT. It is ostensibly inadequate when basic relativistic effects – both special and general – such as causality and covariance, need be accounted for. Such effects are a crucial component of deep space experiments.

Deep space experiments provide a new frontier for Quantum Information Science and for fundamental physics, especially quantum foundations. These experiments will allow us to measure quantum correlations at distances of the order of 10^5km and for detectors with large relative velocities. The Deep Space Quantum Link (DSQL) mission envisions such experiments with photons that involve either Earth-satellite- or intra-satellite communications [3]. These experiments will allow us to test for the first time the foundations of QFT in relation to causality and locality, and by extension to test between different photodetection models appropriate for this novel regime.

Deep space experiments will also enable us to understand the influence of relativistic effects on quantum resources, like entanglement. These effects include relative motion of detectors, retarded propagation at long distance, distinction between timelike and spacelike correlations and gravity gradients. It will also allow us to consider novel types of quantum correlations that are more ”relativistic” in nature, i.e., correlations between temporal variables and qubit variables.

2 The need for a relativistic quantum information theory

Quantum Field Theory, our most fundamental theory for the properties of matter, combines quantum theory and special relativity. In particular, it introduces into quantum theory axioms about the effect of spacetime structure on the properties of quantum systems, especially regarding the causal propagation of signals [4]. In contrast, current QI theories do not incorporate the latter axioms. Their notion of causality, based on the sequence of successive operations on a quantum system, lacks a direct spacetime representation. As a result, the current theory does not make crucial relativistic distinctions, for example, between timelike and spacelike correlations, it does not describe real-time signal propagation, and it ignores relativistic constraints on permissible measurements.

Furthermore, experiments that study causal information transfer or gravitational interaction in multi-partite quantum systems require a QFT treatment of interactions for consistency. A non-QFT description may severely misrepresent the theoretical modeling of the system or the physical interpretation of the results. This point is crucial for fundamental tests of quantum theory, and for quantum communication experiments in deep space.

Current studies of quantum correlations rely on the isolation of specific degrees of freedom—for example, qubits, i.e., two level systems—and the study of correlations of such degrees of freedom. For example, the usual form of Bell-type inequalities refers to properties of qubits, as formulated by Clauser, Horne, Shimony and Holt (CHSH) [5]. This approximation is inadequate when the quantum system is fundamentally described by quantum fields (like photonic qubits) and in a regime where phenomena from delayed propagation and relative motion of reference frames have to be taken into account[1], as in the proposed DSQL experiments.

3 Photodetection theories and quantum resources for long-baseline Bell tests

Consider a long-baseline Bell test, as in the DSQL proposal [3]. It involves a source of entangled photons and two detectors, at large spatial separation and with large relative velocity with respect to each other. A first-principles QFT analysis should allow us to construct a probability density

$$P(X_1, \mathbf{m}_1; X_2, \mathbf{m}_2), \tag{1}$$

where X_i is the spacetime point of detection and $\mathbf{m}_i$ is the photon polarization. The probability density will depend on the initial state of the photons, but also on the distance and relative velocities of the detectors. If we trace out the spacetime coordinates, we will obtain a probability density for $\mathbf{m}_1$ and $\mathbf{m}_2$, allowing us to compare with the CHSH inequalities and to quantify the effects of distance and relative motion. Equally important, from Eq. (1), we can identify novel types of quantum correlation between the qubit degrees of freedom and the times of detection.

To determine Eq. (1) for a specific experiment, we need a general and practicable theory of QFT measurements. The prototype of such a theory is Glauber's photodetection theory that has been immensely successful in quantum optics [9]. In Glauber's theory, the unnormalized probability density (1) is given by

$$P(X_1, \mathbf{m}_1; X_2, \mathbf{m}_2) = \langle\psi|\hat{E}^{(-)}_{\mathbf{m}_1}(X_1)\hat{E}^{(-)}_{\mathbf{m}_2}(X_2)\hat{E}^{(+)}_{\mathbf{m}_2}(X_2)\hat{E}^{(+)}_{\mathbf{m}_1}(X_1)|\psi\rangle, \tag{2}$$

where $|\psi\rangle$ is the quantum state of the field, $E_{\mathbf{m}}$ is the projection of the electric field along a polarization direction given by $\mathbf{m}$, while the suffix +(-) refers to the positive (negative) frequency component of the field.

However, Glauber's theory has a restricted domain of applicability. First, it applies when all detectors are at rest in relation to the photon source. Second, it employs an approximation that misrepresents the retarded propagation of the electromagnetic

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[1] The theoretical reasons for this inadequacy range from the non-invariance of the qubit degrees of freedom under changes of reference frame [6], to causality problems for spatially localized observables [7], and to the inconsistency of the notion of ideal measurements in QFT [8].

field, and for this reason it may face problems with causality when photons travel large distances.

An improvement of Glauber's theory is the Quantum Temporal Probabilities (QTP) method [10], developed by our team, and currently adapted for use in deep space photonic experiments under a grant from the Julian Schwinger Foundation [11]. Like Glauber's theory, QTP expresses quantum probabilities in terms of QFT correlation functions. The QTP formula for the probability density (1) is by

$$P(X_1, \mathbf{m}_1; X_2, \mathbf{m}_2) = \int d^4Y_1 d^4Y_2 K^{i_1j_1}_{\mathbf{m}_1}(Y_1) K^{i_2j_2}_{\mathbf{m}_2}(Y_2)$$
$$\langle\psi|\hat{E}_{i_1}(X_1 + \frac{1}{2}Y_1)\hat{E}_{i_2}(X_2 + \frac{1}{2}Y_2)\hat{E}^{(+)}_{j_2}(X_2 - \frac{1}{2}Y_2)\hat{E}^{(+)}_{i_1}(X_1 - \frac{1}{2}Y_1)|\psi\rangle, \qquad (3)$$

where $K^{ij}_{\mathbf{m}}(Y)$ are kernels that contain all relevant information about the physics of the detector, its state of motion, and the polarization direction of the measurement.

QTP is based on a mathematical distinction between two different roles of time in quantum theory that originates from the work of the principal author on the problem of time in quantum gravity [12]. In particular, KS showed that time is the parameter of evolution in Schrödinger's equation, but it is also a parameter of logical time-ordering. The latter refers to the causal ordering of logical propositions about properties of the physical system. The corresponding parameter t does not coincide with the notion of physical time–as is measured for instance by a clock. Rather, it is an abstraction that takes from the physical concept of time only its ordering properties, i.e., it designates the sequence at which different events happen—the same concept is involved in the time-ordered product of QFT.

QTP leads to different predictions from Glauber's theory for a large class of initial states. Deep space experiments will be able to distinguish unambiguously between the two theories. Other photodetection theories could also be tested, which may be provided, for example, from further research on Unruh-DeWitt detectors [13], or the Fewster-Verch theory of QFT measurements [14].

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