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# DELIVERABLE REPORT

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The main part of the report is related to a review paper published in Rev. Mod. Phys. [PJC1-12]. This work covers various aspects of multi-photon entanglement and its relations with the foundations of quantum technologies and quantum information theory. Multi-photon interference reveals strictly non-classical phenomena. Its applications range from fundamental tests of quantum mechanics to photonic quantum information processing, where a significant fraction of key experiments achieved so far comes from multi-photon state manipulation. The progress, both theoretical and experimental, of this rapidly advancing research is reviewed. The emphasis is given to the creation of photonic entanglement of various forms, tests of the completeness of quantum mechanics (in particular, violations of local realism), quantum information protocols for quantum communication (e.g., quantum teleportation, entanglement purification, and quantum repeater), and quantum computation with linear optics. The scope of the review is limited to "few-photon" phenomena involving measurements of discrete observables. The review covers approximately the last twenty years of development of multi-photon interferometry and quantum technologies based on such phenomena. Also recent results are discussed.

However, out of total over 150 papers that contributed to WP3.5, the bulk of them are addressing or reporting some particular aspect of "interplay between quantum information foundations and technologies and research on quantum entanglement". As this makes impossible to cover all contribution, below only principal papers are listed, which cover broader aspects of this wide field.

[BH1-10] Two important results of independent interest: First, a random quantum circuit gives exponential speed-up in oracle model. This means that quantum speed-up is not accidental, but it is a generic feature of quantum formalism, and it prompts to seek for similar results in circuit model. Second, for the first time it was shown that linear size random quantum circuit gives approximate unitary 3-design. The break-through was to use methods from quantum many-body theory.

[BSP1-11] A hybrid scheme is introduced which combines laser-driven phonon-mediated quantum logic gates in trapped ions with the benefits of microwave dynamical decoupling. It is demonstrated theoretically that a strong driving of the qubit decouples it from the external magnetic noise, and thus enhances the fidelity of two-qubit quantum gates. Moreover, the scheme does not require ground-state cooling, is inherently robust to undesired ac-Stark shifts, and simplifies previous gate schemes thus decreasing the effort in their realization. This quantum gate has just been realised by the Boulder group and is now the world's fastest quantum gate for hyperfine qubits.

[EMG1-12] A famous result by Alan Turing dating back to 1936 is that a general algorithm solving the halting problem on a Turing machine for all possible inputs and programs cannot exist - the halting problem is undecidable. Formally, an undecidable problem is a decision problem for which one cannot construct a single algorithm, which will always provide a correct answer in finite time. Surprisingly, very natural, apparently simple problems in quantum measurement theory can be undecidable even if their classical analogues are decidable. Undecidability appears as a genuine quantum property. The problem is to determine whether sequentially used identical Stern-Gerlach-type measurement devices, giving rise to a tree of possible outcomes, have outcomes that never occur. Implications for measurement-based quantum computing and studies of quantum many-body models are given and suggest that a plethora of problems may indeed be undecidable. The work goes beyond hardness results in quantum complexity theory and shows that natural problems in quantum mechanics can in fact be provably undecidable. For comments see http://phys.org/news/2012-07-classical-problem-undecidable-quantum.html.

[PSB1-12] Quantum systems exhibit particle-like or wave-like behaviour depending on the experimental apparatus they are confronted by. This wave-particle duality is at the heart of quantum mechanics, and is fully captured in Wheeler's famous delayed choice gedanken experiment. In this variant of the double slit experiment, the observer chooses to test either the particle or wave nature of a photon after it has passed through the slits. A quantum delayed choice experiment is reported, based on a quantum controlled beam-splitter, in which both particle and wave behaviour can be investigated simultaneously. The genuinely quantum nature of the photon's behaviour is tested via a Bell inequality, which replaces the delayed choice of the observer. Strong Bell inequality violations are reported, thus showing that no model in which the photon knows in advance what type of experiment it will be confronted by, hence behaving either as a particle or as wave, can account for the experimental data.

[BYH1-13] A scheme to demonstrate loophole-free Bell inequality violation is presented in which the entanglement between photon pairs is transferred to solid state (spin) qubits mediated by cavity QED interactions. As this transfer can be achieved in a heralded way, our scheme is basically insensitive to losses on the channel. This makes it appealing for the implementation of quantum information protocols based on violations of local causality, such as device independent quantum key distribution. Potential experimental realisations may use single atom, colour centre and quantum dot cavity systems.

[CLM1-12] The subset of generalized quantum measurements on finite dimensional systems known as local operations and classical communication (LOCC) is studied. While LOCC emerges as the natural class of operations in many important quantum information tasks, its mathematical structure is complex and difficult to characterize. A precise description of LOCC and related operational classes in terms of quantum instruments is given. The formalism captures both finite round protocols as well as those that utilize an unbounded number of communication rounds. While the set of LOCC is not topologically closed, it is shown that finite round LOCC constitutes a compact subset of quantum operations. Finally, a two-qubit map whose action can be approached arbitrarily close using LOCC, but nevertheless cannot be implemented perfectly, is demonstrated.

[WPZ1-11] One of the essential features of quantum mechanics is that most pairs of observables cannot be measured simultaneously. This phenomenon is most strongly manifested when observables are related to mutually unbiased bases. The connection between mutually unbiased bases and another essential feature of quantum mechanics, quantum entanglement, is studied. It is shown that a complete set of mutually unbiased bases of a bipartite system contains a fixed amount of entanglement, independently of the choice of the set. This has implications for entanglement distribution among the states of a complete set. In prime-squared dimensions we present an explicit experiment-friendly construction of a complete set with a particularly simple entanglement distribution. Finally, we describe basic properties of mutually unbiased bases composed only of product states. The constructions are illustrated with explicit examples in low dimensions. Properties of entanglement in mutually unbiased bases might be one of the ingredients to be taken into account to settle the question of the existence of complete sets. The results are relevant to applications of unbiased bases in experimental realizations of quantum protocols in higher-dimensional Hilbert spaces.

[PJC1-12] Multi-photon entanglement and interferometry, J.-W. Pan et al., Rev. Mod. Phys. 84, 777 (2012).

[BH1-10] Exponential Quantum Speed-ups are Generic, F. G. S. L. Brandao and M. Horodecki, quant-ph/1010.3654.
[BSP1-11] Robust Trapped-Ion Quantum Logic Gates by Microwave Dynamical Decoupling, A. Bermudez, P. O. Schmidt, M. B. Plenio, A. Retzker, arXiv:1110.1870.
[EMG1-12] Quantum measurement occurrence is undecidable, J. Eisert, M. P. Mueller, C. Gogolin, Phys. Rev. Lett. 108, 260501 (2012).
[ME3-12] Positive Wigner functions render classical simulation of quantum computation efficient, A. Mari, J. Eisert, Phys. Rev. Lett. 109, 230503 (2012).
[PSB1-12] A quantum delayed choice experiment, A. Peruzzo, P. J. Shadbolt, N. Brunner, S. Popescu, J. L. O'Brien, arXiv:1205.4926.
[BYH1-13] Proposal for a loophole-free Bell test based on spin-photon interactions in cavities, N. Brunner, A. B. Young, C. Hu, J. G. Rarity, arXiv:1303.6522.
[CLM1-12] Everything You Always Wanted to Know About LOCC (But Were Afraid to Ask), E. Chitambar, D. Leung, L. Mancinska, M. Ozols, A. Winter, arXiv: 1210.4583.
[WPZ1-11] Entanglement in mutually unbiased bases, M. Wiesniak, T. Paterek, A. Zeilinger, arXiv:1102.2080v3.