Report on the PhD thesis

Entanglement Sources and Testing the Foundations of Quantum Theory

by

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Entanglement is the most elementary nonclassical property of multipartite quantum systems and became the resource for novel applications of quantum information processing and quantum enhanced metrology. For describing the common properties of two two-state systems (qubits) a number of tools is well developed by now. Entanglement witnesses, criteria and measures are defined and can be easily used for characterising this property. Yet, there are still a number of subtleties for trustfully observing these properties. The very recent field of device-independent quantum information highlights this fact best. Malfunction of the apparatuses or manipulations from the outside could produce results which only seemingly exhibit entanglement.

More on the foundational side, there are still amazing features to be discovered on very elementary properties of quantum physics. Bell inequalities are well studied by now, however, mostly only the most general, most simple approach is used, which easily hides a multitude of effects to be observed. In his thesis Mohamed Nawareg also is concerned with features of quantum physics which have been overlooked for a long time.

Device independent confirmation of entanglement is a very novel topic in quantum information processing. Mohamed Nawareg tackles in his PhD work this really difficult task. For the first time, he aims to prove the entanglement of two photons without doubt. Recent theory and experiments have shown that data obtained by two observers might be influenced by external adversaries in such a way, that even a product state exhibits entanglement. This can be crucial, if entanglement forms the resource of the quantum communication protocol used as it is the case, e.g., for quantum cryptography according to the Ekert-scheme or for quantum teleportation. The usage of such manipulated quantum channels would be highly disturbed, would be open to attacks on the security of key distribution etc., particularly in view of future developments of quantum repeaters distributed over long distances via several nodes. The new scheme of device independent entanglement witnesses now enables to exclude any manipulation. Given some referee supplying quantum systems to the two observers, the measurement results obtained by the observers on the mutual combination of quantum systems now can prove the entanglement of the initial system distributed over the quantum channel. Remarkably, the quantum systems distributed by the referee do not need to be entangled, they can be in a product state and thus produced locally at the observers' positions. Thus they are not at risk to manipulations of the quantum channel. However, the experimental implementation is quite demanding. Even for a first proof-of-principle experiment, a six photon experiment is necessary, which is at the outmost state-of-the-art. Moreover, in order to show the possibility of this protocol, a high quality experiment is needed, with high fidelity of the produced state and the analysis.

Mohamed Nawareg faced this challenge. For his thesis, in collaboration with the team of Prof. Mohamed Bourennane, he started to develop a new type of down-conversion source, which enables both, high fidelity of the state as well as high brightness of the source. In his thesis, after an introduction to elementary components in quantum interferometry, the development of this source is explained in detail, showing the novelty of the concept. Mohamed Nawareg decides to forgo documentation of test measurements and instead explains in qualitative terms the pros and cons of the different variations of the source. As it is of crucial importance for the experiment to follow, the indistinguishability of the created photons is analyzed and optimized.

Device independent entanglement detection is the central part of Mohamed Nawareg's thesis (chapter 4, also described in the main publication [Nawareg et al, Science Reports 5, 8048 (2015)], which appeared in one of the renowned journals of the Nature publishing group). First the history of entanglement detection leading to the invention of device independent protocols is explained. Referring to the scheme of the set up the measurement procedure and the requirements for the analysis are described followed by the results which really show an excellent agreement with the theory. With this 6-photon experiment Mohamed Nawareg clearly showed his capabilities and set the state-of-the-art for future experiments.

The group at Gdansk University is well known for its numerous, foundational contributions to Bell's theorem. Introducing a very elementary formulation for Bell inequalities, the laid the foundations for new investigations and understanding of this important theorem. Still, there are new facts to uncover. In his thesis Mohamed Nawareg describes a very particular one, namely the formulation of an inequality not using full correlations (chapter 5). This is quite a change in the approach towards Bell inequalities, as it is perfect standard to *only* use the full correlations. This is also a very modern approach and is now also tackled by different groups worldwide. In his thesis and the related publication Mohamed Nawareg and colleagues show, that even measurement results between N-1 parties in turn can be used to test the local realistic properties of N qubit quantum systems. In addition to deriving sufficient conditions for states violating such novel inequalities, the also perform numerical search and optimisation to determine the best state for such tests. Noteworthy, this state has a, to me, quite unexpected symmetry, again highlighting the remarkable properties multi-party quantum systems.

Exclusivity of measurement was recently introduced in the concepts analysing correlations between measurement results. Essentially, this exclusivity principle states that two events which cannot happen together can occur only with individual probabilities whose sum cannot exceed 1. From this amazing connections arise between measurement results obtained for different Bell inequalities. With the high quality entanglement sources developed by Mohamed Nawareg, the team in Stockholm performed a Bell experiment based on an 8 event inequality (chapter 6). In detail and with high precision the exclusivity of the events was confirmed by analysing their probabilities. These data where complemented by results of a contextuality experiment in Rome (described in the appendix). The two experiments have been designed such that their exclusivity graphs have been complementary which should lead to very special relations between the sum of the individual probabilities of the events and the sums of probabilities of all different types of combinations of the events. As the two experiments are truly independently performed, the probability for the combined events results as product of the individual probabilities. Evidently it is not necessary to analyse the individual combinations separately but only their product of probabilities. Their sum was shown to fulfil the exclusivity conditions in all cases. This was only possible by outmost experimental skill to reach one of the highest violations of a Bell inequality so far, thereby improving upon earlier bounds on the exclusivity principle significantly.

Mohamed Nawareg can provide of a very fine, diverse collection of contributions on the foundations of quantum physics and quantum information. His contributions already found and will find attention in the international scientific community and thereby will contribute to the progress in these fields. This thesis documents the quality of Mohamed Nawareg as a researcher in a very positive way. I thus propose to accept this work as PhD thesis and continue with the formal procedure towards awarding the degree.

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