Review of Doctoral Thesis Debashis Saha 'On the fundamental aspects of Quantum Communication'

Doctoral Dissertation of Debashis Saha complies in excess with both statutory and habitual requirements of doctoral dissertations. Both in quality and in quantity of the presented results. In my opinion, the considered research problems are both difficult and of a fundamental importance and the obtained results show vast theoretical knowledge, very good intuition, and great technical skills of Mr. Saha. By the date of the Dissertation submission, the results were publish in five articles in the renown Physical Review A journal, including one article published as a prestigious Rapid Communication, where on top of that Mr. Saha is the first author in a team of two junior researchers. It is also worth mentioning that two of the presented articles have an experimental part. Such mixed works are always of a special value for theoreticians.

The title of the Dissertation very well reflects the subjects it concerns: The fundamentals, quantum communication, and the fundamentals in quantum communication. Recent years have witnessed an unprecedented research activity on the seminal results of J. S. Bell and S. Kochen and E. P. Specker. These are two fundamental theorems, showing how profoundly different are classical and quantum worlds. In brief, the former states that there are correlations predicted by quantum theory, which cannot be simulated by local classical statistics (referred to as non-locality). The later, in a sense more general result, states that one cannot pre-assign definite values to quantum observables in a context-independent manner. Treated for decades as a mere philosophical exercise, both non-locality and contextuality have surprisingly proven not only to challenge our understanding of Nature but also to be useful, or even of a fundamental importance, for practical tasks of information processing and communication.

The presented results can be divided into two general groups:

- Fundamental studies of quantum non-locality and contextuality, where various forms of Bell and non-contextuality inequalities are formulated and studied. Violation of these type of inequalities is, on one hand, a manifestation of a non-classical character and, on the other hand, can have practical implications.

- Quantum communication studies, containing analysis of different modern communication tasks such as Communication Complexity (CC), Dimension Witness (DW), and introduced by the Author and collaborators novel task called Oblivious Communication (OC). All of those tasks share a common paradigm of a sender, sending a message subject to various restrictions to a receiver who tries to decode it. The efficiency being measured via various forms of probability of success. Quite remarkably, and somewhat surprisingly, there is a relationship, to which some of the presented results contribute, between communication efficiency and fundamental aspects named in the point above.

The link between the two groups of results is provided through the notion of contextuality. It is first studied abstractly and then applied to quantum communication protocols. According to my knowledge, the latter aspect has not been studied as much as the relationship between quantum communication and non-locality (in the form of Bell inequality violation).

The Dissertation is in a form of a collection of nine research papers supplemented with a 34-page summary, including the bibliography. The summary is written in English. It is clear, well constructed, and largely self-contained. The bibliography is in my opinion well chosen, containing most of the relevant modern literature as well as historical papers.

Main results In the first group of the results, represented by works [1-4], the most prominent in my opinion is the central result of publication [3]. It shows a new aspect of a particular local/non-local resource trade-off known as monogamy of Bell violation. It states that if two parties violate some Bell inequality, no other party can be correlated with either of them in a such a way as to also violate this inequality. Monogamy is a property of Bell inequality and there are known both monogamous inequalities (like the famous CHSH) as well as non-monogamous. What is shown in [3] is that a non-monogamous inequality can be turned into a monogamous one and, what is most surprising, using purely local contextual inequality. This novel phenomenon is illustrated using so called $\mathcal{I}_{3322}$ Bell inequality. This is a well-known Bell inequality, formulated in 2004 and intensively studied since then, and thus the discovery of its novel, highly non-obvious property, warranted a publication in PRA as a Rapid Communication. It is also worth stressing that the result was published in a small team of two junior researchers with Mr. Saha being the first author and having the leading contribution. Other results in this group include novel findings on the complicated structure of tripartite non-locality [1], showing quantum non-locality from local contextuality using qubits [2], and derivation of contextuality inequalities using only operational notions of contextuality, without assuming determinism [4].

In the second group of results [5-9], the two most prominent ones are two novel links between contextuality and quantum advantage in communication protocols [8,9]. The deep problem approached there is what are the roots of the quantum advantage in communication protocols? The working hypothesis is that it may be contextuality. Working within recently popular semi device-independent framework, which makes only minimal assumptions about the nature of physical systems used for the communication (e.g. fixing the dimensionalities), it is proven in [8] a powerful result that with each Kochen-Specker set of vectors one can associate at least one communication task where a quantum strategy always outperforms classical ones. The first step of the proof is a very intelligently designed communication task, called vertex equality problem, based on a contextuality graph. The result is then proven in two versions: i) bounding the dimension of the underlying Hilbert space and ii) introducing a whole novel communication paradigm called Oblivious Communication, where some of the sender's data are protected from the receiver. The latter version, which in my opinion is the most valuable, required a great deal of sophistication, invention, and some knowledge of the graph theory. Another important result of [8] is a general fact that any advantage in OC implies a violation of one form of

operational non-contextuality, called preparation non-contextuality. Although by the date of the Dissertation submission this work has not been published yet, I feel the result is on the level of high impact journals, e.g. Phys Rev. X.

In article [9], the Authors (two junior researchers with Mr. Saha being the first author and having the leading contribution), present a kind of an inverse implication by showing how quantum advantage can lead to contextuality. They construct for every one-way Communication Complexity task a corresponding one-way OC task, tailored in a such a way that a quantum advantage in the CC task (both in quantum channel and in entanglement assisted classical communication variants) implies an advantage in the corresponding OC task over its classical optimal success probability. Together with the last result of the previous work, this gives a novel and non-obvious implication that a quantum advantage in a CC task leads to preparation contextuality for the corresponding OC task. This implication is father extended to Bell inequalities. A construction of an OC task for any Bell inequality is provided such that a violation of the Bell inequality automatically implies quantum advantage in the corresponding OC task and hence preparation non-contextuality. Up to my knowledge, this is a novel and non-trivial implication. Again, although this work has not been published yet, I feel the result is on the level of high impact journals, e.g. Phys. Rev. Lett. or PRA Rapid Communication. Another results in this group include two works with an experimental part: Publication [5] is dedicated to a complementarity between two quantum strategies in CC tasks (quantum channel and entanglement assisted classical communication), while in work [6] a novel non-classicality test is developed (in a form of a quantum advantage in a certain CC task) for arbitrary low detector efficiencies. Finally, in a technically difficult work [7] a new device independent dimensional witness is constructed, which is particularly suitable for implementations as it employs only binary measurements. The construction is based on a novel communication task called binary Random Access Code and its success probability.

As Mr. Saha states in a short summary section, the question of where does the quantum advantage come from is far from being answered, with the results above presenting some serious hints it might be contextuality. One question that comes to mind in this context is that the contextuality in work [9] was proven in the OC task rather than in the initial CC one. How would the author comment on that? Second, going beyond the scope of the Dissertation, there is another important group of information processing tasks, namely cryptographic protocols. Is it possible to use the presented ideas in the context of semi device-independent cryptography? Can for example contextuality guarantee security?

Final assessment In my opinion the presented Dissertation is of a very high scientific value and complies in excess with both statutory and habitual requirements of doctoral dissertations. The problems considered are both important and difficult. The obtained results are novel and of a high interest, some of them being are already published in a well regarded Phys. Rev. A journal. In addition, Mr. Saha is a co-author of six more articles not included in the presented Dissertation, five of which were published in PRA and QIP. All together this is quite a remarkable achievement for a PhD student, proving high scientific level of Mr Saha's work. Taking all the above in to account, it is my pleasure to recommend Mr. Saha for the next stage

of the PhD conferment procedure and award the presented Doctoral Thesis with summa cum laude distinction.

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Dr hab. Jarosław Korbicz