Summary of PhD thesis

The descriptions of the quantum phenomenon and the macroscopic classical world differ significantly not only in their mathematical formulations, but also in their fundamental concepts and philosophical consequences. The serious pursuit of understanding the nature of quantum reality must arguably invoke a ground common for both classical and quantum theories, on which non-classical features of the later could be discussed. The study of possible ontologies of quantum theory and the features thereof serves this purpose. Apart from its foundational importance, the study of possible non-classical features is of immense significance, because they carry the potential of innovating applications of quantum theory in computation, communication and information processing. In a nutshell, this thesis explores several counter-intuitive non-classical features underlying operational quantum theory, develops many novel directions in quantum communication and establishes significant interconnection between them.

At the beginning of the thesis, we introduce the ontological framework underlying any operational theory along with various notions of non-contextuality and local-causality. Then we move to the main results which are based on nine articles. First, we explore an alternative notion of genuine multipartite nonlocality and analysis the structure of the different sets of tripartite correlation by proposing novel inequalities [1]. Next few works deal with the interconnection between nonlocality and local contextuality. In the simplest scenario of nonlocality where two distant parties share qubit-qubit entanglement, we show that local contextuality plays a role in revealing nonlocality [2]. The other work develops a graph-theoretic method to derive unified monogamy relation between nonlocal and contextual correlations. It also introduces a hitherto undiscovered feature of 'activation of monogamy' of non-monogamous Bell inequality using local contextuality [3]. Next, we address the fundamental concern regarding the assumption of determinism in the Kochen-Specker notion of non-contextuality [4]. We provide a reformulation of non-contextualilty inequalities using a generalized notion of non-contextuality without invoking determinism.

After that, we briefly review two closely related aspects of quantum communication: quantum communication complexity and dimension witness of quantum system in prepare-and-measure scenario. We discuss a particular communication task, namely, 'random access code', with quantum advantage. The advantages offered by quantum resources in communication tasks can be exploited in two distinct ways. The first one involves spatially correlated shared entangled states followed by classical communication of the quantum measurement outcome performed on these states, whereas in the second one, a prepared quantum system is communicated that can be later measured to extract information. The subsequent work shows the nonequivalence between two ways of utilizing quantum resources in a remarkably simple scenario [5]. Then we address two major obstacles to implement device-independent dimension witness of quantum system. One obstacle is the so-called 'detection efficiency loophole' which states that a complete device-independent tests of quantumness can only be conclusive if the detectors used in an experiment provide a detection efficiency above a certain threshold. The other one is the requirement of many outcome quantum measurements to witness a large dimensional system. We propose two new variants of random access code to realize non-classicality for arbitrarily low detection efficiency and to certify arbitrarily large quantum

systems employing only binary outcome measurements, respectively [6, 7]. In the last two articles, we manifest quantum contextuality as a potential resource for several communication tasks. We introduce a general framework of 'oblivious communication' task in which certain information about the sender's input should be secure. It is shown that any advantage in this task over classical channel implies preparation contextuality. Tailored to every logical proof of Kochen-Specker contextuality, we propose communication complexity and oblivious communication tasks with quantum advantage implementing the same set of vectors appearing in Kochen-Specker set [8]. In our most recent work, we convert any advantageous quantum protocol in communication complexity problems to the proofs of preparation contextuality by constructing novel oblivious communication tasks with quantum advantage [9].

Finally, we illustrate an overall perspective on how different notions of non-trivial ontological features of quantum theory and several aspects of quantum communication are inter-connected. We point out our contributions in this picture and conclude by mentioning a few open problems for future research.

References

[1] D. Saha, and M. Pawłowski, *Structure of quantum and broadcasting nonlocal correlations*, Phys. Rev. A 92, 062129 (2015).

[2] D. Saha, A. Cabello, S. K. Choudhary, and M. Pawłowski, *Quantum nonlocality via local contextuality with qubit-qubit entanglement*, Phys. Rev. A 93, 042123 (2016).

[3] D. Saha, and R. Ramanathan, *Activation of monogamy in non-locality using local contextuality*, Phys. Rev. A (R) 95, 030104 (2017).

[4] Z.-P. Xu, D. Saha, H.-Y. Su, M. Pawłowski, and J.-L. Chen, *Reformulating Noncontextuality Inequalities in an Operational Approach*, Phys. Rev. A 94, 062103 (2016).

[5] A. Hameedi, D. Saha, P. Mironowicz, M. Pawłowski, and M. Bourennane, *Complementarity between entanglement-assisted and quantum distributed random access code*, Phys. Rev. A 95, 052345 (2017).

[6] A. Hameedi, B. Marques, P. Mironowicz, D. Saha, M. Pawłowski, and M. Bourennane, *An unconditional experimental test of Nonclassicality*, arXiv:1511.06179 [quant-ph].

[7] M. Czechlewski, D. Saha, A. Tavakoli, and M. Pawłowski, *Efficient device independent dimension witness of arbitrary quantum system employing biary outcome measurement*, arXiv: 1803.05245 [quant-ph].

[8] D. Saha, P. Horodecki, and M. Pawłowski, *State independent contextuality advances one-way communication*, arXiv: 1708.04751 [quant-ph].

[9] D. Saha, and A. Chaturvedi, *Preparation contextuality: the ground of quantum communication advantage*, arXiv: 1802.07215 [quant-ph].