Weak measurements, non-classicality and negative probability

Sooryansh Asthana*[1] and V. Ravishankar†[2]

[1,2]Department of Physics, Indian Institute of Technology Delhi, New Delhi, India-110016.

Keywords: Weak measurements, pseudoprobability, quantum entanglement, quantum discord.

Non-classical attributes of quantum states manifest in various ways, such as quantum coherence in single quantum systems; as non-locality, quantum entanglement and quantum discord in coupled quantum systems. Owing to their resource theoretic importance, many seemingly different approaches have been adopted to derive conditions for different quantum features. Non-classical probability, being a fundamental attribute of quantum mechanics ([1], [2]), should underlie the conditions of non-classicality. Thanks to weak measurements [3], non-classical probability is no longer confined to conceptual domain but has become an experimentally observable quantity, as anomalous weak values.

We propose to establish a robust connection between different features of quantumness, exhibited through notions such as non-locality, entanglement, quantum discord and non-Boolean logic, and the anomalous weak values, as espoused in the concept of weak measurements. This is accomplished by employing the recently introduced concept of pseudo projection [4], and the associated pseudo probability. Pseudo-projections are quantum analogues of classical indicator functions representing joint outcomes of two or more observables. They are Weyl ordered product (completely symmetrised product) of projection operators. Pseudo-probabilities for joint events may be obtained as expectations of the pseudo-projections with the state. Since pseudo-projections have negative eigenvalue, the associated pseudo-probabilities may assume negative value for some states, unlike its classical counterpart. Thus, any negative pseudo-probability is a signature of quantumness. The crucial feature is that negative pseudo-probability for joint outcome of two events can be experimentally realised as anomalous value of a projection operator. Thus, weak measurements provide an experimental avenue to observe negative pseudoprobability and pseudo-projections facilitate an operator description to anomalous weak values.

Since negative pseudo-probability signals quantumness of a system; an interesting question is: what are the sets of pseudo-probabilities which turn negative for states possessing different quantum attributes? In particular, we focus on the anomalous weak values sufficient for (i) Bell-CHSH non-locality in bipartite systems, Svetlichny and Mermin non-locality in multi-party systems, (ii) quantum entanglement in multi-qubit systems, (iii) quantum discord in coupled systems, (iv) quantum coherence in mono-party systems and (v) tests for experimental verification of violation of Boolean logic. We expect that this study puts forth the interconnection between the traditionally understood non-classical aspects of a quantum state and anomalous values of weak quantum measurements. In short, it ties non-classical probability, anomalous weak values and different features of quantumness and opens up new avenues for testing nonclassicality via weak measurements. Since the conditions for different forms of nonclassicality emerge due to particular choices of pseudoprobabilities, we expect conditions for various new features of quantumness to emerge from the framework. All these conditions can be tested through weak measurements.

A pre-print of a part of this work is available at [5].

References

[1] P. A. M. Dirac. *Proc. R. Soc. Lond. A*, 180(980):1–40, 1942.

[2] M. S. Bartlett. *Math. Proc. Camb. Philos. Soc*, 41(1):71–73, 1945.

[3] Y. Aharonov, D. Z. Albert, and L. Vaidman. *Phys. Rev. Lett.*, 60:1351–1354, 1988.

[4] S. Adhikary, S. Asthana, and V. Ravishankar. *Eur. Phys. J. D*, 74(68):68, 2020.

[5] S. Asthana and V. Ravishankar. *arXiv*, 2006.12436.

*sooryansh.asthana@physics.iitd.ac.in

†vravi@physics.iitd.ac.in