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Quantum discord with weak measurements

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HIGHLIGHTS

- Introduced the role of weak measurements in quantifying quantum correlation.
- We have introduced the notion of the super quantum discord (SQD).
- For pure entangled state, we show that the SQD exceeds the entanglement entropy.
- This shows that quantum correlation depends not only on observer but also on measurement strength.

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ABSTRACT

Weak measurements cause small change to quantum states, thereby opening up the possibility of new ways of manipulating and controlling quantum systems. We ask, can weak measurements reveal more quantum correlation in a composite quantum state? We prove that the weak measurement induced quantum discord, called as the "super quantum discord", is always larger than the quantum discord captured by the strong measurement. Moreover, we prove the monotonicity of the super quantum discord as a function of the measurement strength and in the limit of strong projective measurement the super quantum discord becomes the normal quantum discord. We find that unlike the normal discord, for pure entangled states, the super quantum discord can exceed the quantum entanglement. Our results provide new insights on the nature of quantum correlation and suggest that the notion of quantum correlation is not only observer dependent but also depends on how weakly one perturbs the composite system. We illustrate the key results for pure as well as mixed entangled states.

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1. Introduction

Quantum states are fragile to quantum measurements. Yet they try to maintain their privacy. This is exemplified by the fact that it is impossible to know the state given a single quantum system. If we measure an arbitrary quantum state in some orthogonal basis (projective measurement), we loose its coherence. However, if we perform measurement which couples the system and the measuring device weakly, then the system will be perturbed gently and may not loose its coherence completely. Such a scheme was proposed by Aharonov–Albert–Vaidman [1] which is called weak measurement formalism. This gives a weak value of an observable which can take values outside the spectrum of the observable. Remarkably, it has been shown that the weak measurements are universal in the sense that any generalized measurement can be realized as a sequence of weak measurements which result in small changes to the quantum state for all outcomes [2]. The weak-value amplification has found several applications in recent years. To name a few, weak measurements have been exploited for interrogating quantum systems in a coherent manner [3], in understanding the role of the uncertainty principle in the double-slit experiment [4,5], in understanding the macrorealism [6,7], in resolving Hardy's nonlocality [8]. On the practical applications, this has been used for observation of photonic version of the spin Hall effect [9], to amplify the deflection of optical beam in the Sagnac interferometer [10], in the feedback control of quantum systems [11] and even direct measurement of wavefunction of single photon [12]. Recently, it is shown that weak measurements also help in protecting quantum entanglement from decoherence [13].

Understanding the nature of correlations in composite systems is one of the prime goals in the emerging area of quantum information theory. For bipartite states, an entropic measure of quantum correlation known as the quantum discord has been proposed [14]. The quantum discord represents the inaccessible information that cannot be extracted by measurements on one subsystem. It is the difference between the total and the classical correlation [14,15]. It turns out that unlike the entanglement, the quantum discord can be nonzero even for some separable states. This suggests that quantum discord may capture quantum correlation for mixed states that goes beyond the entanglement. The quantum discord has been investigated in a wider context starting from the possibility of giving the power to quantum computation in the absence of entanglement [16], quantum communication such as quantum state merging [17,18], finding conditions for the monogamy nature [19,20], quantum entanglement distribution with separable states [21,22] and has been also experimentally used as a resource [23,24]. Recently, it has been shown that the quantum discord is also a physical quantity, because erasure of quantum correlation must lead to entropy production in the system and the environment [25]. (For a recent review on quantum discord see [26,27].)

Weak measurements are not only important in exploring fundamental physics questions but also have technological implications. In this paper, we ask, can they reveal more quantum correlation for a bipartite quantum system? If they can, then one can exploit this extra quantum correlation for information processing. We prove that the weak measurement performed on one of the subsystems can lead to "super quantum discord" (SQD) that is always larger than the normal quantum discord captured by the strong (projective) measurements. Furthermore, we prove that the super quantum discord is a monotonic function of measurement strength and it covers all the values between the mutual information and the normal quantum discord. Since quantum discord is regarded as a resource our result shows that the super quantum discord can be potentially a more useful resource. We illustrate the notion of the weak measurement induced discord for pure and mixed entangled states. A remarkable feature of the super quantum discord is that for pure entangled states it can exceed the quantum entanglement. In this sense, SQD reveals quantum correlation that truly goes beyond quantum entanglement even for pure entangled states. Our results provide deep insights on the nature of quantum and classical correlations. Thus, quantum correlation is not only observer dependent but also depend on how gently or strongly one perturbs the quantum system. These findings will have several fundamental applications in quantum information processing and quantum technology.

The paper is organized as follows. In Section 2 we introduce the measurement operator formulation of the weak measurements and the notion of super quantum discord. In Section 3 we present the main results of this paper in form of two theorems. In Section 4 we exemplify the notion of super quantum discord for various states and conclude in Section 5.