Postquantum steering

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The discovery of postquantum nonlocality, i.e. the existence of nonlocal correlations stronger than any quantum correlations but nevertheless consistent with the no-signaling principle, has deepened our understanding of the foundations quantum theory. In this work, we investigate whether the phenomenon of Einstein-Podolsky-Rosen steering, a different form of quantum nonlocality, can also be generalized beyond quantum theory. While postquantum steering does not exist in the bipartite case, we prove its existence in the case of three observers. Importantly, we show that postquantum steering is a genuinely new phenomenon, fundamentally different from postquantum nonlocality. Our results provide new insight into the nonlocal correlations of multipartite quantum systems.

Quantum mechanics allows for distant systems to be entangled, that is, correlated in a way that admits no equivalent in classical physics. The strongest demonstration of this phenomena is quantum nonlocality [1, 2]. Performing well-chosen local measurements on separated entangled quantum systems, allows one to observe correlations stronger than in any physical theory satisfying a natural notion of locality, as discovered by Bell. A third form of quantum inseparability is Einstein-Podolsky-Rosen (EPR) steering, which captures the fact that by making a measurement on half of an entangled pair, it is possible to remotely 'steer' the state of the other half. First discussed by Schrödinger [3], this notion was extensively studied in the context of quantum optics [4]. Following a quantum information approach, the concept was put on firm grounds only a few years ago [5], and has attracted growing attention since then. The detection [6, 7] and quantification [8, 9] of steering have been discussed. The concept was also shown to be relevant in quantum information [10, 11], and related to fundamental aspects of quantum theory such as incompatibility of measurements [12, 13].

These phenomena are today viewed as fundamental aspects of quantum theory. Hence a deeper understanding of them provides a fresh perspective on the foundations of quantum theory. In particular, the development of a generalized theory of nonlocality, independent of quantum theory, has brought substantial progress. In a seminal paper, Popescu and Rohrlich discovered the existence of correlations that are stronger than those of quantum theory, but nevertheless satisfying the no-signaling principle, hence avoiding a direct conflict with relativity [14]. This naturally raised the question of whether there exist physical principles (stronger than no-signaling) from which the limits of quantum nonlocality can

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be recovered. Significant progress has been reported [22], notably the discovery of simple information-theoretic and physical principles partly capturing quantum correlations [15, 16, 17, 18, 20, 19, 21], and novel derivations of quantum theory based on alternative (arguably more physical) axioms [23]. In parallel, this research has led to the device-independent approach, a novel paradigm for "black-box" quantum information processing [24, 25].

In the present work, motivated by the insight that the study of postquantum nonlocality has brought, we ask whether the phenomenon of steering can be generalized beyond quantum theory (like nonlocality can), but nevertheless in accordance with the no-signaling principle. We first start by discussing the case of two observers (where one party, Bob, steers the other, Alice): here a celebrated theorem by Gisin [26] and Hughston, Josza and Wootters [27] implies that postquantum steering does not exist. We then move on to the multipartite case, and show explicitly that postquantum nonlocality implies the existence of postquantum steering when three observers are involved. This brings us to the main question and result of the paper, whether postquantum steering that is fundamentally distinct from postquantum nonlocality exists. We discuss what precisely would constitute such a phenomenon, and show that indeed postquantum nonlocality and postquantum steering are genuinely distinct phenomena.

Our results motivate the study of the latter as a new way to study the structure and limitations of quantum correlations. Indeed, the use of the concept of steering allows us to investigate quantum correlations while keeping the local structure of quantum theory. Notably, our results highlight the fact that the structure of the Hilbert space describing tripartite quantum systems is fundamentally different compared to the bipartite case, in accordance with previous work [28, 29]. For instance, in the case of nonlocality it was shown that a natural extension of Gleason's theorem is possible in the bipartite case, but fails for multipartite systems [28]. In the context of entanglement theory, every pure bipartite entangled state admits a canonical form (Schmidt decomposition), however the situation turns out to be more complex in the multipartite case [29]. It would be very interesting to understand whether the above observations are intimately related to each other and to the existence of postquantum steering.

Our work raises several questions. For instance, it would also be interesting to find further examples of postquantum steering, and understand how generic the phenomenon is. Moreover, given the strong information-theoretic power of certain postquantum nonlocal correlations, it would be relevant to investigate what can be achieved using postquantum steering. In particular, can postquantum steering enhance protocols involving quantum information, for instance better quantum teleportation or remote state preparation?

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