Post-quantum steering

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Abstract

Steering is one of the phenomena observed in Nature that cannot be explained merely from classical physics. Together with nonlocality and contextuality, these phenomena show that classical mechanics is not enough to describe our current view of the world, and that another theory is indeed required. Quantum theory then succeeds in explaining not only steering, but also nonlocality and contextuality. However, there is no guarantee that quantum mechanics is the ultimate theory, and hence a study of supra-quantum phenomena is still in order. In the case of nonlocality and contextuality, such an analysis has been widely performed. Indeed, the discovery of post-quantum 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 show that the phenomenon of post-quantum steering may also be defined while still complying with basic physical principles such as no-signalling. This phenomenon so far has not been noticed since bipartite steering scenarios cannot display it: in order to find post-quantum steering, multipartite steering scenarios are required. We first study cases where post-quantum steering arises as post-quantum nonlocality and then also show that post-quantum steering with no post-quantum nonlocality is in principle possible. Hence, post-quantum steering represents a genuinely new effect.

It is arguably a well accepted fact that quantum mechanics allows systems in Nature to share correlations that are stronger than those allowed by classical physics. First discussed by Einstein, Podolsky and Rosen [1], this phenomenon is due to the existence of entangled states that have no classical analogue. Discovered by Bell [2], the strongest demonstration of this phenomenon is quantum nonlocality: 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 [3]. Einstein-Podolsky-Rosen (EPR) steering is another form of quantum inseparability, 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 Schrodinger [4], this notion was extensively studied in the context of quantum optics [5], and only recently attracted growing attention from a quantum information approach [6].

Steering is usually studied in bipartite settings, where two parties share a state. One of the parties (say, Alice) is fully trusted, in the sense that we assume that the physics of what happens in her lab is fully described by quantum mechanics and that she has full knowledge of the operations that she performs on the state. Hence, she could in principle perform quantum tomography and characterise her marginal of the shared state. The other party (say, Bob), however, is not trusted, in the sense that no assumptions can be made on the measurement devices or the physical processes happening in his lab[1]. Hence the only reliable information from Bob's actions is the measurement statistics on his share of the system. The object of study in such a scenario then is the set of conditional states $\sigma_{b|y}$ (usually called assemblage) that Bob remotely prepares on Alice's lab by performing measurements on his share of the system: y denotes his measurement choice and b the obtained outcome.

In our paper we explore whether Alice could certify that the assemblage of conditional states in her lab cannot arise via performing measurements on a quantum state, in the sense that Bob would require more-than-quantum resources to prepare them. This is similar in spirit to the study of supra-quantum nonlocality, where development of a generalized theory of nonlocality independent of quantum theory has brought substantial progress on the understanding of the foundations of quantum physics. Indeed, 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 [7]. This naturally raised the question of whether there exist physical principles (stronger than no-signaling) from which the limits of quantum nonlocality can be recovered. Besides leading to the discovery information-theoretic and physical principles capturing essential properties of quantum theory, such research has also led to the device-independent approach, a novel paradigm for "black-box" quantum information processing [8, 9].

A similar study of post-quantumness in steering scenarios is hence still in order. In such a setup one is allowed to investigate quantum correlations while keeping the local structure of quantum theory. In the present work, motivated by the insight that the study of post-quantum nonlocality has brought, we ask whether the phenomenon of steering can be generalized beyond quantum theory (much like nonlocality can be), but nevertheless in accordance with the no-signaling principle. We start by discussing the case of two observers, where one party, Bob, steers the other, Alice. Here a celebrated theorem by Gisin [10] and Hughston, Josza and Wootters [11] implies that post-quantum steering does not exist. Hence, every 'no signalling' assemblage prepared by Bob on Alice's side can be explained by him performing measurements on one part of a shared bipartite quantum state. Hence, in order to explore the phenomenon of post-quantum steering multipartite scenarios are required.

There are different ways of defining steering scenarios for many parties, mainly because there are several ways of choosing who are the trusted ones. In this work we focus on one of the simplest cases, where there are three parties only one of which is trusted (Alice), and show explicitly the existence of post-quantum steering. Interestingly, we are able to find post-quantum assemblages from which no post-quantum correlations in the Bell sense can arise via Alice further measuring her system, hence proving the existence of post-quantum steering which does not reduce to post-quantum nonlocality. Therefore, post-quantum steering is a genuinely new phenomenon, fundamentally different from post-quantum nonlocality. In these steering scenarios hence the use of post-quantum resources can only be witnessed by looking at the assemblage, but is not apparent at the level of the probability distribution.

An interesting aspect of this work is to highlight a fundamental difference between bipartite and multipartite quantum correlations, as well as between the structure of the Hilbert space describing bipartite and multipartite quantum systems, which goes alongside previous findings [12, 13]. 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 [12]. 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 [13]. It would be very interesting to understand whether the above observations are intimately related to each other and to the existence of post-quantum steering.

Finally, our work raises several questions. From a foundational scope, while our example

[1]This is similar to the device-independent approach adopted in nonlocality scenarios

of post-quantum steering was shown not to give rise to post-quantum nonlocality for arbitrary projective measurements, it is natural to see if this is also the case when general non-dichotomic quantum measurements are considered. It would also be interesting to find further examples of post-quantum steering, and understand how generic the phenomenon is. From an applied viewpoint (more related to the topic of this conference), given the strong information-theoretic power of certain post-quantum nonlocal correlations, it would be relevant to investigate what can be achieved using post-quantum steering. In particular, whether post-quantum steering can enhance protocols involving quantum information, for instance better quantum cryptography, teleportation or remote state preparation. In this sense I believe that qcrypt attendees would benefit from learning about this post-quantum effect.

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