Abstract

The quantification of quantumness is necessary to assess how much a physical system departs from a classical behaviour and thus gauge the quantum enhancement in operational tasks such as information processing and computation. For arbitrary multiparticle systems, the quantification of quantumness typically involves nontrivial optimisation problems, and may require demanding tomographical techniques. We have developed an experimentally feasible approach to the evaluation of geometric measures of quantumness, according to which the distance from the state of the system to a suitable set of classical states is considered. Our approach provides analytical results for particular classes of mixed states of N qubits, and computable lower bounds to global, partial, and genuine multiparticle entanglement, as well as to quantum coherence, for any general state. For global and partial entanglement, as well as quantum coherence, useful bounds have been obtained with minimum effort, requiring local measurements in just three settings for any N. For genuine entanglement, a number of measurements scaling linearly with N is required. We have demonstrated the power of our approach to estimate and quantify different types of multiparticle entanglement in a variety of N-qubit states useful for quantum information processing and recently engineered in laboratories with quantum optics and trapped ion setups.

We have then focused on the open dynamics of quantumness. Those who work on quantum technologies are indeed always looking for ways to manage decoherence, which occurs when a quantum system unavoidably interacts with the surrounding environment. We have shown that all distance functions, which respect natural assumptions of invariance under transposition, convexity, and contractivity under quantum channels, give rise to geometric quantifiers of quantumness which exhibit the peculiar freezing phenomenon, i.e., remain constant during the evolution of a particular class of states of an even number of qubits each independently interacting with a non-dissipative decohering environment, in the case of quantum coherence and discord-type correlations, and of two qubits undergoing collective dephasing, in the case of entanglement. Even more, in the case of quantum coherence, we have seen that such freezing phenomenon is observed experimentally in a two-qubit room temperature nuclear magnetic resonance quantum simulator. These results demonstrate from first principles that freezing of geometric quantumness is independent of the adopted distance and therefore universal, thus paving the way to a deeper physical interpretation and future practical exploitation of the phenomenon for noisy quantum technologies.

Furthermore, we have investigated the nature of spontaneous symmetry breaking in

complex quantum systems by conjecturing that the maximally symmetry-breaking quantum ground states are the most classical ones corresponding to an ordered phase. We have made this argument quantitatively precise by showing that the ground states which realise the maximum breaking of the Hamiltonian symmetries are the only ones that: I) are always locally convertible, i.e. can be obtained from all other ground states by local operations and classical communication, while the reverse is never possible; II) minimise the monogamy inequality for bipartite entanglement; III) minimise discord-type correlations for all pairs of dynamical variables and are the only ground states for which the pairwise discord-type correlations vanish asymptotically with the intra-pair distance.

Finally, we have investigated how the non uniqueness of a bona fide measure of distinguishability defined on the quantum state space affects the quantum speed limits and can be exploited in order to derive improved bounds. Specifically, we have established an infinite family of quantum speed limits valid for unitary and nonunitary evolutions, based on an elegant information geometric formalism. Our work unifies and generalises existing results on quantum speed limits, and provides instances of novel bounds which are tighter than any established one based on the conventional quantum Fisher information. We have illustrated our findings with relevant examples, clarifying the role of classical populations versus quantum coherences in the determination and saturation of the speed limits. These results can find applications in the optimisation and control of quantum technologies such as quantum computation and metrology, and might provide new insights in fundamental investigations of quantum thermodynamics.