THESIS DEFENSE: Certifying quantum resources in many-body systems from accessible observables

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09:00

Elements Room

Almost a hundred years ago, the modern quantum theory was born and, from the outset, challenged classical physics with revolutionary concepts. Arguably, quantum entanglement, which describes correlations that cannot be explained classically (e.g. via statistical mechanics) is the most notable of them. On the other hand, quantum entanglement is an essential resource to certain information processing tasks and fuels emergent technologies such as quantum computing, simulation or sensing. Hence, the evaluation of a state's resource content, as prepared in a device, is a prerequisite to assess the advantage it may provide in these quantum-enhanced applications. Over the last decades, the second quantum revolution brought new experimental capabilities to generate and control massively correlated states in many-body systems. Such advances have also posed remarkable theoretical challenges. Most of the entanglement measures and detection approaches do not scale well and are extremely hard to implement as the system's size grows towards the macroscopic scale. This thesis primarily aims at developing reliable theoretical tools to certify the preparation of entangled states and other quantum correlations in many[1]body systems from accessible observables. In doing so, we reconcile various information-theoretic measures to the laboratory by constructing witnesses that can be readily tested in current experiments. In the course of this work, we address the certification of a number of resources related to quantum entanglement ranging from coherence to Bell nonlocality. A common aspect among these resources is their convexity, namely, the fact that the resource content cannot be produced nor amplified by mere statistical mixing of dif[1]ferent states. This observation is also a key technical property for almost all of our contributions. Here, we focus on those many-body systems that are most easily probed by permutation-invariant or collective observables, such as spin ensembles or spinor Bose Einstein condensates. In this respect, the symmetries of the observables can be leveraged to construct entanglement criteria with a more favorable scaling. The resource content of a physical system is certified from the statistics it produces. Within the quantum formalism, such statistics ar encoded in the density matrix, which is reconstructed based on finite information fro experimentally available probes. We start the thesis by outlining a practical machine-learnin assisted protocol to improve and denoise the inference of such statistics in realisti scenarios. Subsequently, we discuss the certification of metrologically useful entanglemen by introducing a simple algorithm to evaluate the minimal quantum Fisher informatio compatible with a set of iv arbitrary mean values. Our approach enables to systematicall tighten well known spin squeezing parameters and reveal the sensing power of many-bo y states with minimal experimental effort. Next, we address the detection of entangleme t from averages and uncertainties of collective observables by formulating a single conditi n testing a number of witnesses, including those proposed in the past such as the generaliz d spin squeezing inequalities. We apply our approach to unveil new entanglement witness s tailored to Bose-Einstein condensates based on Zeeman sublevels populations. We al o discuss, to some extent, the witnessing of the Schmidt number, the central biparti e entanglement measure, using similar observables. Then, we tackle the converse problem f detecting separable states from mathematical techniques based on invertible positive map . The last part of the thesis is devoted to Bell nonlocality, one of the strongest forms f nonclassicality beyond quantum entanglement. We first scale Bell dimension witness, i. . criteria whose violation signals the impos[1]sibility of explaining the inferred statistics with a Hilbert space of a given local dimension, to the many-body regime. In particular, we propo e that the violation depth of a specific three-outcome Bell inequality can be used to robust y certify the number of qutrits in an ensemble. We close the thesis by presenting a data-driv n approach to detect Bell nonlocality from one- and two-body spin correlations averaged ov r all permutation of parties. This methodology allows us to discover tighter Bell inequaliti s tailored to spin squeezed states and many-body spin singlets of arbitrary spi

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