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Optimal certification of many-body entanglement

M2 internship => PhD Thesis — Quantum many-body physics, quantum information

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Entanglement is "*the* characteristic of quantum mechanics" (E. Schrödinger, 1935) as well as the crucial factor enabling most of the future quantum technologies implementing quantum computation, quantum simulation and metrology [1]. The investigation of entanglement in quantum *many-body* systems has become a central topic of interest for multiple reasons. At a most fundamental level, scaling up the size of quantum systems that can be controllably prepared in highly non-classical states makes it possible to probe the putative existence of a "quantum-to-classical boundary", at which classical behavior emerges even in systems which are governed by quantum mechanics. In terms of more immediate goals, the controlled creation of many-body entanglement is the central functionality of future devices such as quantum simulators and quantum computers, whose promise is fundamentally based on the hardness of simulating highly entangled states with a classical computer; as well as of the most advanced class of future quantum sensors, which aim at exploiting the highest sensitivity of entangled states to the application of external fields. Access to large-scale many-body entangled states opens the door to the investigation of quantum dynamics far from equilibrium; of equilibration vs. metastability vs. many-body localization; of the effect of an environment on quantum coherence, and the existence of phase transitions in non-equilibrium stationary states; to cite a few relevant examples.

For fundamental as well as technological reasons, the certification of many-body entanglement, and the understanding of its spatial structure and nature, is therefore a crucial task of modern quantum physics. Such a task is intrinsically complex, because, to be efficient, it should be done in a time and with resources scaling polynomially with the number of degrees of freedom. This implies that detailed knowledge of the quantum state is intrinsically excluded, as it would require an exponentially expensive tomographic reconstruction. Entanglement certification based on a limited (polynomial-size) amount of information on the quantum state is called *entanglement witnessing* [2], and it is the central goal of this project.

Our team has recently developed a variational protocol which allows one to reconstruct the optimal entanglement witness [3] based on a (polynomial) set of observables — accessible experimentally via quantum simulation, or numerically via a classical simulation of the quantum many-body system of interest. Our protocol builds systematically the separable (i.e. not entangled) quantum state which approximates at best the set of observables: this scheme is provably a convex optimization problem, which admits one unique minimum that can be found in polynomial time. If the optimal separable state fails to reproduce the desired observables, the amount of its failure allows one to reconstruct the optimal entanglement witness, namely an inequality valid for all separable state which is violated most strongly by the set of observables. This scheme represents the core of *scalable optimal certification of many-body entanglement.*

The project aims at applying this scheme to equilibrium as well as non-equilibrium quantum states, in relationship with current experiments on cold-atom quantum simulators. Possible goals of the PhD work will be 1) the obtention of entanglement criteria for equilibrium and non-equilibrium states of systems of large-S spins on a lattice with long-range (dipolar) interactions, modeling the physics of ultracold magnetic atoms trapped in optical lattices [4,5]; 2) the study of entanglement criteria for systems of Rydberg atoms in arrays of optical tweezers, realizing models of interacting qubits [6]; 3) the study of entanglement criteria for multi-mode quantum optics systems, specifically for the output states of photonic circuits such as those realizing boson sampling [7].

A general overarching theme will be the use of observables based on two-body correlations vs. the use of higher-order correlations / higher moments of the distribution of a collective observable. Establishing a classification of quantum states (e.g. those realized during a non-equilibrium evolution) in terms of the type of correlations certifying entanglement is a fundamentally open problem, capturing the essence of the "detectability" of entanglement.

Our theoretical work is framed within a theory-experiment collaboration (funded by a French and a European project) with a network of experimental and theory teams including the Laboratoire de Physique des Lasers, Paris XIII; the Center for Ultracold Atoms and Quantum Gases, University of Innsbruck (Austria); the 5th Institute of Physics of the University of Stuttgart (Germany); the CNR-INO in Pisa (Italy); the Institute for Photonic Sciences (Spain); and the Institute of Physics of the Polish Academy of Sciences (Poland).

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