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Entanglement and quantum non-locality in ultracold atoms

M2 internship => PhD thesis project

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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]. From a fundamental point of view, entanglement is the necessary condition for the striking manifestations of non-locality in quantum mechanics. One of the them is the paradoxical ability to control the state of a system by measuring another system which is spatially separated from the former (the so-called quantum *steering*). An even more fundamental manifestation of non-locality (Bell's nonlocality) implies that measurement results on composite quantum systems are inconsistent with any model of "local realism", postulating classical correlations among the measurement outcomes, as manifested by the violation of Bell's inequalities [3].

The investigation of entanglement in quantum *many-body* systems has become a central topic of interest for multiple reasons. On the fundamental side, it is crucial to scale up the size of quantum systems that can be controllably prepared in highly non-classical states, with the ambitious goal of approaching the (so far mysterious) quantum-to-classical boundary, at which classical behavior emerges even in systems which are governed by quantum mechanics. This endeavor has also an obvious technological bonus, because 1) highly non-classical states of large quantum systems cannot be efficiently stored and manipulated using classical computers, and therefore their controlled realization in experiments opens the path to the experimental quantum simulation of intractable quantum many-body models (quantum simulation); and 2) highly non-classical states have an augmented sensitivity to external fields which makes them suitable for high-precision sensing, beating the capabilities of classical measurement apparatuses (quantum metrology).

In this project we propose to explore theoretically some highly non-classical states of quantum many-body systems which are relevant to state-of-the-art experiments on ultracold atoms. The latter represent to date the most controlled, flexible and scalable platform to engineer quantum many-body systems starting from the elementary constituents [4]. In particular we propose the investigation of entanglement and quantum non-locality in two systems: 1) quantum spin Hamiltonians on a lattice with long-range (dipolar) interactions, modeling the physics of ultracold magnetic atoms trapped in optical lattices [5]; and 2) Hamiltonians describing bosonic particles that move on a lattice, and that strongly interact via either short-range (contact) or long-range (dipolar) interactions [4]. In these systems highly entangled states can be realized either at *thermal equilibrium*, especially when tuning a parameter Hamiltonian close to a quantum phase transition; or *far from equilibrium*, during the real-time evolution which follows the initialization of the system in non-entangled state.

The main goal of the project will be twofold

1) the formulation of effective criteria to detect entanglement, steering and Bell's non-locality in the states naturally produced at equilibrium or far from it in the experiments; and in particular the reconstruction of the spatial structure of such quantum correlations, either in real space or in momentum space;
2) the study of effective experimental protocols to produce non-classical correlations that are naturally detected in experiments. After a study of equilibrium systems, we shall devote particular attention to quench dynamics in dipolar spin models realized in Mott insulators of magnetic atoms [5] as a source of entanglement in real space; and to dynamical instabilities (such as those realized in quenched quantum gases with dipolar interactions [6] or under periodic driving [7]) as a potential source of detectable entanglement and further quantum correlations in momentum space.

To investigate the spatial structure of entanglement and quantum non-locality (steering and Bell's correlations) we shall make use of advanced theoretical approaches based on world-line quantum Monte Carlo for the investigation of equilibrium quantum systems [8]; and on semiclassical approaches — generalized Bogoliubov theory and (modified) spin-wave theory [9,10] — as well as (fully quantum) variational quantum Monte Carlo [11,12], for the study of non-equilibrium physics. The theoretical work is framed within a close collaboration with Fabio Mezzacapo (ENS de Lyon), and 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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