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PhD Thesis Booklet

Correlations and dynamics in interacting cold atomic systems

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Introduction

The rapid experimental progress of the past decades opened up unprecedented possibilities to study strong correlations in a wide range of cold atomic systems. This breakthrough led to the experimental realization of Bose-Einstein condensates and Fermi degenerate gases [Anderson et al., 1995, Davis et al., 1995, DeMarco et al., 1999], and allowed to confine these gases to quasi one or two dimensional geometries [Görlitz et al., 2001, Paredes et al., 2004, Kinoshita et al., 2004], or to load them into optical lattices [Greiner et al., 2002]. The precise control over the trapping potential, combined with the ability to tune the interactions between the atoms by magnetic fields, paved the way to use these systems as quantum simulators, to explore the correlated structure of various quantum phases [Bloch et al., 2008], and to investigate the propagation of correlations in non-equilibrium states in detail [Polkovnikov et al., 2011, Eisert et al., 2015, Langen et al., 2013]. These developments in experimental techniques have triggered an increasing theoretical interest both in the structure of strongly correlated equilibrium phases and in the out of equilibrium dynamics of isolated quantum systems. The ability to experimentally investigate non-equilibrium physics in cold atomic settings has raised fundamental questions, such as the emergence of statistical physics in closed quantum systems, and revealed its intimate connection to the spreading of correlations [Deutsch, 1991, Rigol et al., 2008].

In spite of the progress stimulated in theoretical physics, the detailed analysis of correlated states remains challenging and still largely unexplored, especially in non-equilibrium situations. Motivated by the need of more insight into the behavior of these complex systems, my thesis focused on the correlated structure of various cold atomic systems, both in and out of equilibrium.

Objectives

My first goal was to gain more insight into the equilibrium correlations induced by the interplay of interaction induced quantum fluctuations, confinement and particle number conservation, relevant for trapped, closed cold atomic systems. To this end I studied the equilibrium structure of a trapped interacting Bose gas, and I analyzed the momentum correlations in detail.

My second objective was to demonstrate that the most widespread experimental tool to study cold atomic systems, the time-of-flight imaging, contains a lot more information than extracted before, and allows the detailed characterization of quantum states, both in and out of equilibrium.

As a third goal, I wanted to gain more insight into the entanglement production in many-body systems. To this end I planed to study in detail the entanglement entropy generation in a simple, experimentally accessible cold atomic system.

Finally, I intended to study the fate of the quantum coherence, transferred from a coherently moving particle to its initially disordered environment. We wanted to show that a single particle can build-up significant correlations in its environment, in contrast to the common expectation that this coherence is quickly destroyed by dephasing.

Methods

I have combined analytical considerations with numerical simulations, in order to study the equilibrium correlations and the non-equilibrium dynamics of various cold atomic systems. I investigated the correlated structure of low dimensional Bose-Einstein condensates in the framework of Luttinger-liquid theory, and by applying a particle number preserving Bogolibov approximation. For studying the out-of-equilibrium dynamics in different cold atomic settings, I have used exact diagonalization complemented with a semi-classical approximation, as well as a real time Monte Carlo simulation.

New scientific results

The main results of my thesis are summarized in the thesis points below.

1. By studying the momentum correlations in a two dimensional, harmonically trapped interacting Bose gas, I demonstrated that the coherent transfer of particles between the single mode condensate and the non-condensed cloud amounts to an *anti-correlation* dip between particles of opposite wave numbers $\mathbf{k}$ and $-\mathbf{k}$ for $|\mathbf{k}| \sim 1/R_c$, with R_c denoting the typical size of the condensate. In contrast, for larger wave numbers $|\mathbf{k}| \gg 1/R_c$, I found weak positive correlations, in accordance with the Bogoliubov theory of homogeneous condensates.

   This result is published in paper [1].

2. I introduced a new characterization scheme for quantum states, relying on measuring the *full distribution*

of the spatially resolved density of the expanding gas. I benchmarked this method on an interacting one dimensional Bose gas in the quasi-condensate regime. In the ground state, I found that the finite momentum fluctuations, observed at large distances, manifest in a crossover from exponential to a Gamma distribution upon decreasing momentum resolution. In contrast, the zero momentum particles, reflecting the fluctuations of the quasi-condensate, follow a Gumbel distribution, which remains observable at small but finite temperatures. I demonstrated that this characterization scheme also reflects (pre-)thermalization processes after an interaction quench.

These results are published in paper [2].

3. By studying the time evolution of the entanglement entropy of coupled single-mode Bose-Einstein condensates in a double well potential, I demonstrated that this dynamics reflects the coherent oscillations of the condensates by displaying entropy oscillations on the top of a steady entropy production on short time scales. I showed that the entropy reaches a stationary value in the long time limit due to dephasing, in spite of the lack of equilibration. I demonstrated that this saturated limit reflects the dynamical self-trapping transition of the system, and it can be understood in terms of a classical microcanonical ensemble.

   These results are published in paper [3].

4. I participated in the analysis of the non-equilibrium dynamics of a hole created in a two dimensional, non-interacting, completely disordered infinite temperature spin bath, demonstrating that a single hole in-

duces long-lived correlations between the surrounding spins. I showed that this dynamics can be understood in terms of the random walk paths of the moving hole, and of the rearrangement of the spins along this trajectory. I found that the spin correlations satisfy a sum rule due to the conservation of the total spin, ensuring the build-up of both ferromagnetic and antiferromagnetic correlations.

These results are published in paper [4].

Publications

Publications related to thesis points:

[1] Izabella Lovas, Balázs Dóra, Eugene Demler, and Gergely Zaránd, *Quantum-fluctuation-induced time-of-flight correlations of an interacting trapped Bose gas*, Phys. Rev. A **95**, 023625 (2017).

[2] Izabella Lovas, Balázs Dóra, Eugene Demler, and Gergely Zaránd, *Full counting statistics of time-of-flight images*, Phys. Rev. A **95**, 053621 (2017).

[3] Izabella Lovas, József Fortágh, Eugene Demler, and Gergely Zaránd, *Entanglement and entropy production in coupled single-mode Bose-Einstein condensates*, Phys. Rev. A **96**, 023615 (2017).

[4] Márton Kanász-Nagy, Izabella Lovas, Fabian Grusdt, Daniel Greif, Markus Greiner, and Eugene A. Demler, *Quantum correlations at infinite temperature: The dynamical Nagaoka effect*, Phys. Rev. B **96**, 014303 (2017).

Further publication:

[5] Balázs Dóra, Izabella Lovas, and Frank Pollmann, *Distilling momentum-space entanglement in Luttinger liquids at finite temperature*, Phys. Rev. B **96**, 085109 (2017).

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