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Bernhard Rauer

Non-Equilibrium Dynamics Beyond Dephasing

Recurrences and Loss Induced Cooling in One-dimensional Bose Gases

Doctoral Thesis accepted by
the Atominstitut, TU Vienna, Vienna, Austria

Springer

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Supervisor's Foreword

The question of whether an isolated quantum many-body system relaxes is a central problem at the interface between microscopic quantum dynamics and statistical physics. It is of high relevance in many diverse fields, ranging from decoherence in quantum information and metrology to the complex dynamics in high-energy physics and cosmology. Moreover, relaxation processes are intimately related to the question if and how the classical world at the macro-scale can emerge from the unitary quantum evolution at the micro-scale.

The thesis of Bernhard Rauer investigates a series of questions that are highly contested in this context: How does an isolated quantum many-body system relax? To what extent and through which processes is the memory of an initial state erased during time evolution? How does a classical ensemble description in the sense of statistical physics emerge from the underlying quantum evolution when an actual environment is absent?

Over the last years, ultracold gases have emerged as an ideal model system to study these questions. They are nearly perfectly isolated and a large set of tools is available to manipulate and probe their many-body physics in a controlled setting. One-dimensional (1d) gases are especially interesting in that context. They exhibit very rich dynamics and can be compared to well-studied theoretical models. An especially interesting aspect is that in many 1d systems a large number of conserved quantities constrain the evolution and have a profound effect on their relaxation processes.

In his thesis, Bernhard Rauer investigates relaxation dynamics in degenerate 1d Bose gases of ^{87}Rb atoms, confined on an atom chip. The thesis studies two main topics: the first being concerned with the creation of these systems in the laboratory. In experimental realizations of 1d Bose gases, the temperature of the system needs to be brought below the minimal energy of transverse excitations to confine dynamics to the desired single dimension. However, this leads to an exponential suppression of thermalizing collisions which should force thermalization to stop. Nevertheless, evaporative cooling, which highly depends on efficient thermalization processes, works surprisingly well within the 1d regime and experiments reach temperatures far below the freeze-out of thermalizing collisions. Why these low temperatures can be reached remained a mystery for the last 10 years. Bernhard Rauer investigates the cooling process in detail and presents a semi-classical mechanism that describes the cooling as a loss-driven reduction of fluctuations under a continuous dephasing of the involved phononic excitations. This model is in good agreement with the experimental findings and finally provides a solution to the cooling conundrum. Remarkably, the contribution of atomic shot noise that is expected to become relevant at low temperatures seems to be absent in the measurements.

The second focus of the thesis lies in the out-of-equilibrium dynamics following a quench. Extending Poincaré's recurrence theorem to the quantum domain, any finite quantum system should at some point return arbitrarily close to its initial state. In large many-body systems, however, the complexity of the many-body eigenstates and their spectrum leads to exceedingly long recurrence times. Yet, Bernhard Rauer was able to observe recurrences of coherence in the post-quench relaxation dynamics of a pair of 1d Bose gases. The key to the experiment lies in the insight that one cannot observe the many-body eigenstates directly, but can only observe much simpler few-body observables. These observables can be linked to an effective quantum field theory description through the system's collective modes. Controlling the dispersion of these collective modes, in this case phonons, allows to observe recurrences in experimentally accessible quantities. Performing the post-quench relaxation experiments in a box-shaped potential results in commensurate phonon frequencies such that the observation of their rephasing becomes feasible, even for systems of thousands of particles. Both the recurrence time and its scaling with the size of the system are well described by a low-energy Luttinger liquid model. In contrast, the measured damping of the recurrence signal stems mainly from phonon-phonon scattering processes mediated by terms beyond the low-energy effective field theory description. The presented experiment sets a beautiful example of how rephasing can be used to probe many-body processes at times beyond the initial dephasing dynamics, opening up a new window to study quasi-particle interactions in such systems. Another remarkable feature of the experiment is that, even though the system apparently relaxes to a classical (generalized) Gibbs ensemble, coherence underneath this classical statistical physics cover leads to a return of the initial state at the point of the recurrence. This illustrates the intricate connection between the unitary evolution in quantum many-body systems and the description of their relaxed state in terms of statistical mechanics.

Vienna, Austria
March 2019

Prof. Dr. Hannes-Jörg Schmiedmayer

Abstract

Out-of-equilibrium dynamics in complex quantum many-body systems is a vast topic of research touching many different areas of physics. One of the most versatile experimental platforms to investigate these effects are ultracold atoms, due to their flexibility and easy isolation from the environment. In this thesis, we investigate non-equilibrium dynamics of one-dimensional (1d) Bose gases realized with ultracold ^{87}Rb atoms on an atom chip. Focusing on phenomena emerging on timescales beyond the typical dephasing times of excitations, we report on the observation of recurrences and the finding of a novel cooling mechanism.

A recurrence, the dynamic return of a system to its initial state, can generally not be observed in large systems as the complexity of their excitation spectra shifts its appearance to prohibitively long times. Yet, by realizing a commensurate spectrum in a pair of near-homogeneous 1d Bose gases, recurrences in their low-energy dynamics can be observed on experimentally accessible timescales. We demonstrate this by initializing two gases in a phase coherent state by coupling them through a tunneling barrier before suddenly ramping the coupling to zero. The subsequent dynamics is monitored by matter-wave interferometry, providing access to the relative phase field between the gases. After an initial dephasing dynamics, we observe multiple recurrences of the coherent initial state due to a rephasing of the underlying excitations. Additionally, analyzing the damping of these recurrences, we detect otherwise elusive scattering effects between excitations.

Furthermore, we investigate the dynamics of a 1d Bose gas under a continuous loss of particles. With thermalization strongly inhibited in these systems, standard evaporative cooling is rendered ineffective; yet, we still observe a substantial cooling effect. This cooling is driven by a novel mechanism that relies neither on an energy selective extraction of particles nor on efficient thermalization channels. Instead, it proceeds through a loss-induced reduction of density fluctuations and a continuous dephasing of the involved excitations. For experiments with 1d Bose gases, this mechanism fills an important gap in the understanding of the state preparation and the limits of cooling.

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Contents