Invited Paper

Relaxation of an out-of-equilibrium closed quantum systems: experimental observations of decay of turbulence and the stages to reach equilibrium

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ABSTRACT

Starting with a Bose-Einstein Condensate of Rb atoms in equilibrium, the System is brought to turbulence and left to relax under the occurrence of reactions from the introduced excitations. The typical phenomena of the evolution to establishment of the turbulence states are observed. After excitation is removed, the system begins to relax, giving way to diverse phenomena such as the presence of non-thermal fixed points, pre-thermalization and finally equilibrium with or without the reconstitution of the condensate depending of the quantity of injected energy. The work paves the way for the study of the thermalization of an out-of-equilibrium many-body quantum system.

Keywords: Quantum Turbulence, Relaxation, Non-Thermal Fixed points, pre-thermalization, revival of the condensate phase.

1. INTRODUCTION

Investigations of non-equilibrium quantum systems are an important challenge. Despite many theoretical contributions to the topic, which have been occurring over several decades of study, the experimental part is still taking its initial steps. Bose-Einstein condensates – BEC, with trapped atoms constitute an excellent system for such studies [1]. There are several aspects that must be observed during the temporal evolution of a quantum system removed from equilibrium and left to evolve spontaneously. When we use turbulence to take the system out of equilibrium, during evolution, we begin by triggering the processes that allow the establishment of turbulence. These involve cascades that allow observing the moment regions with a power law dependence, inertial region. The dependence of the spectral energy on the moment k in this region allows us to have indications about the type of turbulence we are dealing with. Over time, the reaction of the vortices and other introduced excitations will allow progress to be made with evolution and now the system must begin its journey towards a new state of equilibrium. Various mechanisms occur such as the presence of scalability around the so-called Non-Thermal -Fixed Points (NTFP), pre-thermalization and finally the reconstitution of the condensate. During the evolution, the behavior of the n(k) , the population distribution in the moment classes, allow us to understand the sequence of evolution stages involved in the process towards equilibrium. In this work, we present experimental observations that allow us to analyze the various phases of evolution of the non-equilibrium condensed system, until it reaches its new state of equilibrium [2].

2. EXPERIMENTAL SYSTEM AND RESUTLS

The starting point of the experiment involves producing a condensate of Rb-87 atoms, a fact that is achieved using previously described techniques. Atoms can be trapped in different hyperfine states, producing samples with different characteristics in terms of spatial distribution. Once with a condensation of about 5 10^5 atoms, a collection of coils placed along one of the directions of the Ioffe-Pritchard trap allows the introduction of small fractions of rotation and deformations that lead to the introduction of vortices, solitons and collective modes. After about 30 ms of excitation, the sample is saturated with excitations that now progress to the turbulence state. Depending on the excitation time and its amplitude, excitations are introduced in different quantities, producing turbulence states of different levels. Once the excitation is complete, the system is left to evolve and at the end of the t_{hold} time, by time of flight, the distribution in momentum density n(k) is observed. Figure 1 shows the simulations showing the level of introduced excitations and their evolution, as well as a typical set of measurements of the distribution of n(k) over time [3]. Analyzing the distribution of momentum for atoms close to the smallest modes (smallest values of k), we can see the evolution of the condensate, from its starting point, going through several stages of evolution, until reaching the equilibrium state again, with a new condensate or thermal cloud formed. A diagram showing this evolution is represented in figure 2, where the migration of low-momentum atoms

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is observed during the initial moments, where cascades, and other evolutionary phenomena occur, until the reversal of the migration of atoms, with the reformation of the condensate

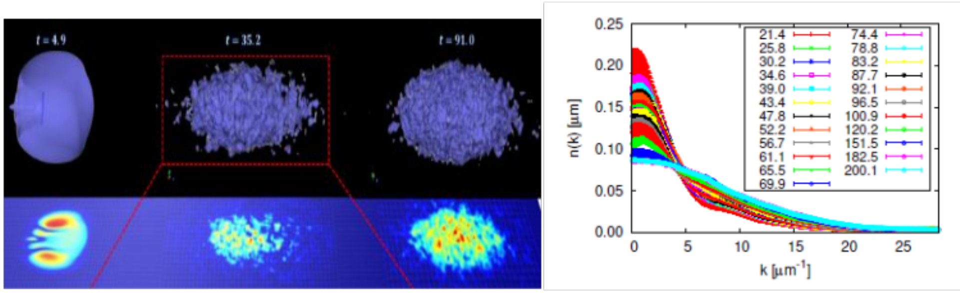

Fig 1- (a) – Simulation showing the level of excitations introduced in the sample. (b) Typical n(k) measurements at different evolution times in ms.

With the help of several experimental-theoretical developments, we can identify several stages, such as the presence of NTFP [4], prethermalization and finally the formation of BEC. Through this evolution, we can investigate how the quantum system can process the introduced energy that took it out of equilibrium and reformulate the new equilibrium condition. Several different situations can be analyzed and promote the provision of information that enables the understanding of the relaxation of out-of-equilibrium quantum systems [2].

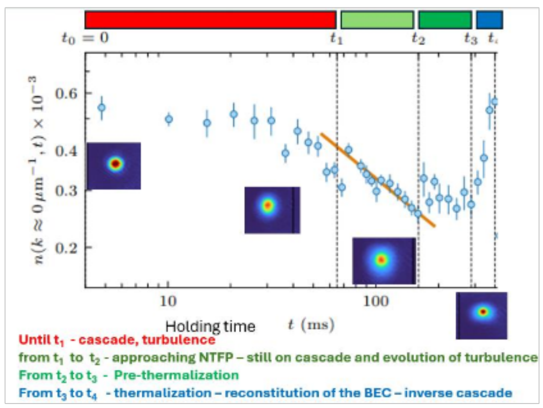

Fig. 2 – Time evolution for the low momenta class on the n(k). Interpretations for the different stages is provided in the figure.

There is a further stage of evolution above t_4 that we are now investigating. The interpretation of NTFP, pre-thermalization are based on models and information presented in literature. The final blow-up part, representing the final formation of the BEC in new conditions, has being explained through an inverse cascade effect calculated in reference [5] based on four wave -missing processes in a system with dominance of wave-turbulent behavior, which we believe is what we have after the final stages of evolution.

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