Project No: 330076
Project Acronym: Quantum quench
Project Full Name: Universality in the Non-Equilibrium Dynamics of Strongly Correlated Quantum Systems

Marie Curie Actions

Final Report

1 FINAL PUBLISHABLE SUMMARY REPORT

The general objective of the proposed research was to study the out of equilibrium dynamics of strongly interacting systems after they are taken out of equilibrium by a quantum quench, in order to understand under what conditions and how isolated quantum systems equilibrate or thermalise. These questions that lie at the heart of the foundations of statistical physics can now be studied experimentally in cold atomic gases due to the spectacular progress seen in the last decades in these experimental techniques.

The simplest way to create an out of equilibrium situation is a "quantum quench", when a parameter of the system is abruptly changed after which the system is let evolve unitarily. Integrable systems play a distinguished role in this setup, because due to the large number of conserved quantities they possess, their time evolution is highly constrained and as a consequence they cannot reach thermal equilibrium this way. Instead of the thermal Gibbs ensemble, the Generalised Gibbs Ensemble (GGE) featuring the conserved quantities was proposed to capture the steady state of integrable systems. Since in the real world no perfectly integrable system exists, it is of crucial importance to understand the effect of integrability breaking perturbations.

The researcher studied the entanglement properties of the stationary state after a quantum quench in the experimentally relevant 1D Bose gas from zero to infinite repulsion, and showed that the entanglement entropies become extensive thermodynamic entropies of the Generalised Gibbs Ensemble (GGE) describing the steady state.

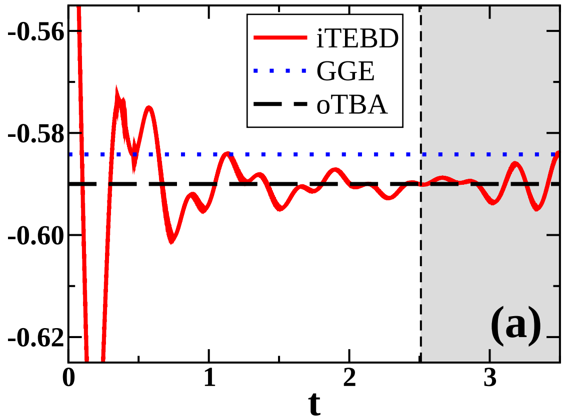
In real cold atom experiments, the atomic gas is never homogeneous but trapped by an external potential. With his collaborators in Pisa, the researcher investigated the effect of a trapping potential on quantum quenches and found a two-step relaxation process.

He also studied the effect of starting the time evolution from an excited state as opposed to a ground state in the transverse field Ising chain. Analysing various correlation functions, the GGE was shown to be valid. The entropies of the diagonal ensemble and the GGE were computed and compared. The results were published in an article that was selected to be part of the highlights of the year of the journal (Europhysics Letters).

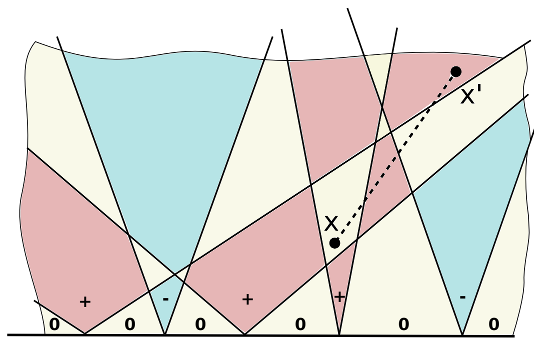
The most important result and the clearest manifestation of the transfer of knowledge is the work done in collaboration with another research group at the host university. In this work it was shown that, contradicting the general belief held by researchers in the field, the Generalised Gibbs Ensemble (GGE) fails to capture the steady state after quenches in the anisotropic Heisenberg (XXZ) spin chain, by comparing the GGE predictions to the actual time evolution computed numerically. At the same time, an alternative theoretical description was shown to agree with the numerical simulation (see Fig. 1a). This result, published in Physical Review Letters, has had a great impact in the community, it led to vivid discussions at conferences and inspired several publications.

A quantum quench injects an extensive amount of energy in the system which amounts to creation of quasiparticles. In the semiclassical method the quasiparticles follow classical trajectories and quantum mechanics play a role in their collisions (see Fig. 1b). The researcher studied the non-equilibrium time evolution of the sine-Gordon field theory by adapting the semiclassical technique to the non-equilibrium situation. In a cold atom setting, the computed quantities correspond to correlations of the relative phase between two one dimensional bosonic condensates coupled by quantum tunneling. These correlations can in principle be measured by matter wave interferometry. The article containing these results is currently under review. The researcher is now developing further the semiclassical approach into a numerical technique by fully taking into account the quantum nature of the collisions. The method will be applicable to various quantum field theories as well as quantum spin chains.

The proposed research plan involved the development of a novel non-perturbative numerical method to study the out of equilibrium time evolution of strongly correlated quantum field theories and the effect of integrability breaking on the relaxation. Two versions of the so-called Truncated



(a) Numerical simulation (iTEBD) of the time evolution of correlation function $\langle\sigma_1^z\sigma_2^z\rangle$ of the magnetisation (red line). The horizontal blue dotted line shows the GGE prediction and the black dashed line the prediction of our alternative theoretical description.



(b) Semiclassical configuration of domain walls (time flows in the vertical direction).

Figure 1

Space Approach have been developed for the Ising field theory. The first one exploits the free fermion representation (Truncated Fermionic Space Approach), in which the basis and the matrix elements of operators are simple and intuitive. The second one is an improved version of a code which existed as part of the knowledge base of the host group. It is a Truncated Conformal Space method based on the Virasoro algebra which has been improved by fully exploiting the chiral factorisation of the calculations in the conformal basis. This improvement led to a code which is multiple times faster than the previous version and requires much less memory. It is capable of generating Hamiltonian matrices in a million dimensional Hilbert space. The advantage of the second method over the fermionic approach is that it can be easily generalised to more complicated perturbed conformal field theories, for example the sine-Gordon model.

The method was benchmarked by analysing integrable quenches of the transverse field in the Ising field theory, for which exact analytic results are available in the literature. The Loschmidt echo (fidelity), the statistics of work done in the quench, and time evolution of expectation values of local operators have been computed and compared with the theoretical results with excellent agreement.

After these tests the researcher started to study the effect of integrability breaking by adding a longitudinal magnetic field. The perturbed system has very interesting and rich dynamics which, somewhat unexpectedly, reveal the interplay between the non-equilibrium situation and the weak confinement of the domain walls by the magnetic field. The paper reporting these results is currently under preparation, and will be sent to a high profile journal. It has the potential to have a great impact in the community.

The researcher also published two papers that are not connected directly to quantum quenches. One is about dynamical correlations in a quantum field theory corresponding to the scaling limit of the transverse field Ising chain in a longitudinal magnetic field and describing an experimentally studied cobalt-niobate compound. The results were published in the Physical Review Letters.

In another work the researcher and his collaborators found an intriguing connection between the celebrated Kardar-Parisi-Zhang stochastic growth equation and a non-equilibrium problem in the sine-Gordon quantum field theory. The publication was selected as a highlighted article of the journal.