Reg. No: 2023/49/N/ST3/01033; Principal Investigator: inż. Jakub Marcin Pawłowski

Quantum systems close to integrability

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One of the most widely disputed problems in modern physics is the reconciliation of irreversible thermodynamics with unitary, time-reversible dynamics predicted by quantum mechanics. **In other words, it is the question of whether a generic, isolated quantum system can and will 'forget' about its initial, non-equilibrium state.** In recent years, this problem has attracted the attention of many physicists, especially taking into account experimental evidence of the loss of information, or thermalization, in isolated systems. Understanding this phenomenon is a crucial first step to controlling it, and perhaps to the creation of sought-after, robust systems which do not exhibit such behavior. After all, 'forgetting' about the initial state is equivalent to scrambling quantum information and decoherence, which has been known for a long time to be one of the most important hindrances to a functional and scalable quantum computer. Given the multitude of possible applications of such a device, both purely scientific and commercial, achieving control of thermalization in isolated quantum systems could be the next groundbreaking discovery.

Our present understanding of thermalization in such systems is based on the Eigenstate Thermalization Hypothesis (ETH), which relates long-time properties of measurable quantities to the predictions of statistical mechanics. As of now, there is no rigorous proof of the validity of ETH for a generic system and we need to rely mostly on numerical studies. To approach this issue from a different perspective, we turn our attention to systems that explicitly violate ETH. There are a few known classes of models that do not follow ETH-predicted thermalization: **quantum integrable models**, systems with 'scars', which freeze thermalization for some infrequent, but physically relevant states, quantum time crystals with broken time-translation symmetry, and systems with many-body interactions together with some form of a disorder. **As the thermalization in those systems is slowed down or even completely stopped, in principle they could preserve information about the initial state for an arbitrarily long time, which should prove useful for the emerging field of quantum devices.** This behavior is in strong contrast with what is usually observed in interacting, many-body systems, namely fast dynamics on the time scales of tens of femtoseconds.

Unfortunately, microscopic integrable models form a very idealized subset of many-body physics, and more realistic systems are expected to be described by **nearly integrable systems**, containing some non-negligible perturbations that impact integrability. The immediate question is whether the integrability is in any way robust against such perturbations. Or can we at least ensure that the thermalization is slowed down enough to allow practical applications? In classical mechanics, a positive answer to this question is given in the language of Hamiltonian perturbation theory and the famous KAM theorem. As of now, there are no similar results in quantum mechanics. It is expected that in the limit of infinite system size, arbitrarily small perturbation should restore chaotic dynamics and ensure thermalization. However, there are some reports about surviving traces of integrability, for example in the form of residual, quasiconserved quantities. **Therefore, the main goal of this project is the investigation of yet mostly unknown border between ETH and ETH-violating regimes**. We shall adopt a twofold approach to this problem, based on the so-called local integrals of motion (LIOMs), that is conserved quantities whose existence entails a violation of ETH-predicted thermalization, provided there are enough of them. Of course, they cannot exist in non-integrable systems in a strict sense, so they are approximated by **local slowly relaxing operators** (LSROs), which are no longer conserved and decay with a finite relaxation time. We want to study the relaxation of physically relevant observables in nearly integrable systems in terms of LSROs and understand the timescales governing their decay, especially whether there is always a single relevant timescale or a more complicated, multi-scale relaxation scenario is necessary. Many realistic systems are not limited to only short-range interactions or only one dimension, thus we are also going to examine systems with long-range interactions or quasi-1D systems, looking for signs of integrability in otherwise nonintegrable models. Parallel to those two tasks we shall pursue an improved numerical scheme for the detection of LIOMs and LSROs which could overcome the limitations imposed by the exponentially growing complexity of numerical calculations in quantum systems.

We believe that understanding thermalization and its characteristic timescales in systems close to integrability is an important problem, especially because of new emerging experimental methods and quantum technologies, which will allow direct probing of this intermediate regime and perhaps harnessing its unique properties.