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On Quantum Seas.

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Summary

On Quantum Seas

The rules of quantum mechanics, though hard to grasp intuitively, are clear and well understood. Yet, the behavior of large collections of even the simplest interacting quantum components are hard to predict.

As paradigmatic examples one often considers models built from two-state quantum systems or qubits. These, like a classical bit, have two states (say *on* and *off*, or *up* and *down*) but according to the superposition principle of quantum mechanics cannot just exist in one or the other but also in a mixture of both. As a result, the number of elementary states grows exponentially with the number of qubits, which underlies many of the difficulties in computing collective behavior for large collections of components in quantum mechanics. Two-state systems can represent for instance the magnetic moment of spin-1/2 particles and are the foundation for understanding magnetism. Depending on how these quantum spins are allowed to interact the resulting collective behavior can differ wildly, with the possibility to observe phase transitions and crossover behavior depending on the system parameters.

One job of condensed matter physics is to develop methods to understand collective behavior in physically meaningful interacting systems of quantum components such as spins. In this thesis, we focus on what happens when we put quantum spins on a one-dimensional line such that neighboring spins interact—forming so-called spin chains. In particular, we build on existing methods to effectively describe such quantum spin chains and similar one-dimensional systems to study the influence of additional features hitherto not included in the theory. For example, we study what the difference is in terms of observable quantities when we focus on the last spin of a spin chain which has an abrupt end as compared to the same measurement on a spin somewhere in the bulk (the latter already being described by the theory we build upon).

Most of the effective methods in describing one-dimensional systems such as spin chains have focussed on the ground state—the state at absolute zero temperature—which is important for understanding the equilibrium properties.

Part of this work is concerned with certain states of the system that are far from equilibrium, but in some respects are still very similar to the ground state. This similarity is reflected in the ability to use suitable extensions of the effective theory which has been developed for the ground state to again compute in-principle measurable quantities. *In principle*, because it is not yet clear whether such states can actually be created in any experimental setup. However, the predictions can be tested against numerical simulations of the model systems—a strategy which is often used to verify predictions of effective methods in lack of experimental results. The theoretical construction of the states under consideration resembles that of the well-known Fermi sea ground state of fermions but with a 'splitting' of the sea. Therefore we have coined the term Moses sea to describe such states.

Although the class of Moses sea states that has been studied in the final chapters of this thesis has no direct experimental relevance yet, the inspiration to study such states has in fact come from a famous experiment known as the Quantum Newton's cradle. In this experiment, a sequence of laser pulses has been used to give the atoms in a bosonic gas a kick in two opposite directions. The cloud of atoms is observed to split into two blobs and then recollide according to the direction of the elongated optical trap. Surprisingly, such oscillating behavior is then continued for thousands of times without clear signs of thermalisation. Similar experiments with the confining trap being more two- or three-dimensional results in quick relaxation towards a single blob. The absence of thermalization is related to the properties of collisions in one dimension for which a sequence of two-body collisions cannot redistribute momenta, and the presumably very infrequent occurrence of three-body collisions in the system. We have constructed a mathematical simulation of the experiment using an idealized description of bosons in one dimension known as the Lieb-Liniger model which captures the most important details. The state after the laser pulse has some similarities with a Moses sea, but also some marked differences. However, the application of effective approximate methods and effective theory not often used in a non-equilibrium setting provides interesting insights in this case as well. The oscillations of the blobs of gas for instance correspond well to the oscillations of classical particles rolling back and forth in a parabolic potential without interacting with each other—a surprisingly simple effective description for a complicated many-particle interacting quantum system.

The part of this thesis with most direct experimental relevance concerns a system of gold atoms deposited on a semi-conductor (germanium) surface. This so-called Au/Ge(001) system has been considered a promising candidate for the observation of one-dimensional physics due to the atomic chain-like structures that are observed to appear on the surface after the gold is deposited.Measurements of the electronic properties before and after the deposition have led researchers to conclude that the atomic chains host one-dimensional electronic states well-described by the effective one-dimensional theory that for instance also describes the properties of spin chains (a so-called Tomonaga-Luttinger liquid). Detailed experimental investigations of collaborators at the University of Amsterdam and the University of Twente however reveal that this conclusion is in conflict with the measurements. In particular, certain symmetry properties of the electronic states conflict with a one-dimensional scenario while they are reproduced by an elementary model based on the symmetries of the surface after the gold deposition. Although some questions remain, the most likely explanation of all observed properties is that the gold-induced electronic system is effectively two-dimensional with strong effects of disorder and interactions.

Quantum mechanics, despite its counter-intuitive nature, is one of the most successful theoretical achievement of humankind to explain natural phenomena. The study of model systems of interacting components helps in understanding emergent phenomena from quantum mechanics and reveals how classical behavior can result from complicated quantum interference effects. In the meantime, accurate predictions can be obtained and tested against experimental observations. Additionally, the discovery of new types of behavior may lead to new aplications. The possibility to observe actual one-dimensional systems is one of the more recent developments and promises an exciting interplay between theory and experiment in years to come. Similarly, the study of out-of-equilibrium quantum systems is still developing and is bound to lead to novel insights in the near future. This thesis has added a few little pieces in these directions.