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Quantum Collective Behavior in Low Dimensions

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Summary

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This thesis aims at describing the effects of collective behavior in low-dimensional quantum many-body systems that are closely related to experimental settings. In Chapter 2 we describe the evolution of a localized electronic spin in a semiconductor quantum dot under the influence of interactions with its environment. We focus on the influence of direct interactions with the nuclear spins in the underlying substrate, and on the role of a changing configuration of the nuclear spins mediated by dipole interactions among themselves. We consider the case for which the confined electronic spin, also referred to as the central spin, is initialized into a quantum superposition of two states, and study how the relative phase between these superpositions is influenced by the nuclear environment, leading to an eventual loss of coherence. We find that for large external magnetic fields the change in configurations of the nuclear spins due to their mutual interactions has the strongest influence on the loss of coherence of the central spin. On the contrary, for lower external magnetic field the direct interactions become the dominant source of decoherence for short times.

In Chapter 3 collaborative work is presented that revolves around a low temperature scanning tunneling microscope experiment, performed at Delft University of Technology. Using a scanning tunneling microscope cobalt atoms are manipulated to form linear chains. Even though cobalt atoms behave as spin-3/2 objects, their low energy properties can be described using an effective spin-1/2 theory. We show that this also holds for a group of cobalt atoms interacting in a one dimensional chain, and that the experiment realizes a well-known textbook quantum many-body model: the spin-1/2 XXZ Heisenberg model in a transverse field. For this model a quantum phase transition is predicted in the thermodynamic limit of an infinitely large system with an infinite amount of particles. However, precursors of this transition from an antiferromagnetic phase to a paramagnetic phase as a function of external transverse field can be seen for finite size systems. By comparing the experimental data with a theoretical model we show that the experiment demonstrates signatures of this finite size onset of quantum criticality as the length of the cobalt chains is increased.

In Chapter 4 and 5 we consider the theoretical modeling of the Quantum Newton's Cradle experiment [27], which can be seen as the quantum analogue of the classical Newton's cradle. In this experiment, similar to its classical counterpart, an initial situation far from equilibrium is created by transferring momentum

to the bosonic atoms with a so-called Bragg pulse. In Chapter 4 we describe a situation similar to the experiment for the case of infinitely repulsive bosons that are brought out of equilibrium by a very short and strong Bragg pulse. The description of infinitely repulsive bosons is aided by mapping the problem to a dual description of free fermions, which is specific to one dimension. We study the difference between a gas of bosons that evolves in a homogeneous background and in a harmonic trapping potential. We observe that the effects associated to the harmonic trapping potential only set in after hard-core interactions have already caused a prerelaxation of the gas similar to the homogeneous gas.
We furthermore discuss the efficiency of momentum transfer through finite duration Bragg pulses on hard-core bosons, and conclude that protocols designed for free bosons, perhaps not surprisingly, perform significantly less well for strongly interacting bosons.
In Chapter 5 we extend our description of Bragg pulsed Bose gases to include finite interaction effects. We describe strong but finite repulsive bosons by extending the aforementioned duality to weakly interacting fermions. We compute the time evolution of observables after a strong Bragg pulse by using a self-consistent mean-field approximation. During the time evolution density oscillations are enhanced with respect to the case of hard-core bosons, which is consistent with a weaker repulsive interaction. We furthermore observe that the dynamics of the density as well as the momentum distribution function is slowed down as a consequence of a decreased sound velocity in the system due to finite interactions. Possible extensions of this method to include external trapping potentials and other pulse sequences are briefly discussed.