Relaxation and decoherence in quantum spin system
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Chapter 1

Introduction

Quantum spin systems are of much interest recently, not only because of their relevance to magnetic (nano) materials in general but also because of their relation to the quantum computation and quantum information in particular. The quantum computer promises to be more powerful than classical computers in solving some particular problems such as integer factorization, database search, and simulation of quantum systems. Quantum information combines communications and cryptography and is considered to be absolute secure. In the physical realization of quantum computation and quantum information, one major problem is keeping the components of the computer or communication channel in a coherent quantum state. The interaction with the external world reduces the coherence (phase relations) between the states of the quantum system. This effect, called decoherence, destroys the unitary transformations that are essential for quantum information processing. Therefore, the study of relaxation and decoherence in quantum spin systems is necessary to understand the basic phenomena that are at play.

Quantum spin systems are rather complicated many-body systems and except for some special cases their time evolution cannot be calculated analytically. With the help of powerful modern computers and efficient algorithms, we can simulate the dynamics of the system directly by solving the time-dependent Schrödinger equation. A lot of useful information can be extracted from these simulations, information that may be relevant for the development of a theory or experimental study of these systems.

In this thesis, we will focus on two different quantum spin problems. The first concerns the relaxation and decoherence of a central system of two spins
that is coupled to a spin-bath environment. This problem is not only related to the progress of the physical realization of quantum computer and quantum information, but also addresses fundamental conjectures of decoherence theory. Another topic is the stability of domain wall and its interaction with spin waves in spin 1/2 chain, which is relevant to the critical phenomena and quantum communication in quantum spin systems.

The contents of each chapter are the following:

In Chapter 2, we present the details of the physical model and the algorithms that we use to perform the computer simulations.

In Chapter 3, we study the relaxation and decoherence in a system of two antiferromagnetically coupled spins that interact with a spin-bath environment, which is initially prepared in its ground state. Systems are considered that range from the rotationally invariant to highly anisotropic spin models, for instance, the couplings among the bath spins or between them and the central two spins, can be isotropic Heisenberg or Ising-like. The interactions have different topologies and values of parameters that are fixed or allowed to fluctuate randomly. We explore the conditions under which the two-spin system clearly shows an evolution from the initial spin-up -spin-down state towards the maximally entangled singlet state. We demonstrate that frustration and, especially, glassiness of the spin environment strongly enhances decoherence of the two-spin system.

In Chapter 4, we continue the study of decoherence of two coupled spins that interact with a frustrated spin-bath environment in its ground state. The central system can be either ferromagnetic or antiferromagnetic. The conditions under which the two-spin system relaxes from the initial spin-up -spin-down state towards its ground state are determined. It is demonstrated that the symmetry of the coupling between the two-spin system and the environment has an important effect on the relaxation process. In particular, we show that if this coupling conserves the magnetization, the two-spin system readily relaxes to its ground state whereas a non-conserving coupling prevents the two-spin system from coming close to its ground state.

In Chapter 5, we study decoherence of two coupled spins that interact with a chaotic spin-bath environment which initially is prepared in a random superposition of all the basis states of the environment. This state corresponds to the equilibrium density matrix of the environment at infinite temperature. It is shown that connectivity of spins in the bath is of crucial importance for decoherence of the central system. The previously found phenomenon of
two-step decoherence (V. V. Dobrovitski et al, Phys. Rev. Lett. 90, 210401 (2003)) turns out to be typical for the bath with a slow enough dynamics or no internal interactions. For a generic random system with chaotic dynamics, a conventional exponential relaxation to the pointer states takes place. Our results confirm a conjecture that for weak enough interactions, the pointer states are eigenstates of the central system.

In Chapter 6, we demonstrate that magnetic chains with uniaxial anisotropy support stable structures, separating ferromagnetic domains of opposite magnetization. These structures, domain walls in a quantum system, are shown to remain stable if they interact with a spin wave. The value of the phase shift of spin waves passing through a domain wall was found to be proportional to the angle by which the magnetization of domain wall rotates in the film plane (R. Hertel et al, Phys. Rev. Lett. 93 257202 (2004)). We find that a domain wall transmits the longitudinal component of the spin excitations only. Our results suggest that continuous, classical spin models described by Landau-Lifshitz-Gilbert equation cannot be used to describe spin wave-domain wall interaction in microscopic magnetic systems.

In Chapter 7, we study the real-time domain-wall dynamics near a quantum critical point of the one-dimensional anisotropic ferromagnetic spin 1/2 chain. It is known that the ground state of this model in the subspace of total magnetization zero supports domain wall structures. However, if we let the system evolve in time from an initial state with a domain wall structure and this initial state is not an eigenstate, it must contain some excited states. Therefore, the question whether the domain wall structure will survive in the stationary (long-time) regime is nontrivial. In this chapter, we focus on the dynamic stability of the domain wall in the Heisenberg-Ising ferromagnetic chain, and by numerical simulation, we find the domain wall is dynamically stable in the Heisenberg-Ising model. Near the quantum critical point, the width of the domain wall diverges as $(\Delta - 1)^{-1/2}$. We also show that the domain wall profiles rapidly become very stable as we move away from the quantum critical point.