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Decoherence of a quantum system coupled to an *XY* spin chain: Role of the initial state of the spin chain

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ABSTRACT

We study the decoherence of a coupled quantum system consisting of a central spin and its correlated environment described by a general *XY* spin-chain model. We make it clear that the evolution of the coherence factor sensitively depends on the initial state of the environment spin-chain. Specially, the dynamical evolution of the coherence factor of the central spin is numerically and analytically investigated in both weak and strong coupling cases with initial state set as the ground state of the initial Hamiltonian $H_E^{(\lambda_i)}$ at time $t = 0$ which may be different from the evolving Hamiltonian $H_E^{(\lambda_e)}$ for time $t > 0$, as well as set as the thermal equilibrium state. In both weak and strong coupling cases, we show that the evolution of the coherence factor with initial state being the ground state of the initial Hamiltonian can be approximated by a Gaussian. Particularly, in the strong coupling regime the coherence factor oscillates rapidly under a Gaussian envelope. The width of the Gaussian decay (envelope) is presented in detail.

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1. Introduction

Docoherence refers to the process through which quantum coherent pure states irreversibly transformed into classical mixed ones. It is induced by unavoidable coupling of a quantum system with its surrounding environment. Usually, the coupling will destroy the coherence between the pointer states of the system in a short time [1], and thus is a major obstacle in quantum information processing (QIP) in which the coherent entangled states were used as resources [2,3]. Therefore, the study of docoherence is important for understanding quantum physics and the implementation of QIP.

Generally the decoherence process depends on both the effective Hamiltonian and the initial state of the environment. The effects of the effective Hamiltonian on the decoherence have been extensively studied in previous references [4–19]. Especially, in the vicinity of the quantum critical point (QCP) of the effective Hamiltonian, dramatic manifestation of the decoherence has often been found. Hence much work have been focused on the critical properties of the decoherence [7,9,10,15–19]. Whereas, the dependence of the decoherence process on the initial state of the environment has rarely been mentioned [20,21] and thus will be studied in this paper. In particular, we will focus on the Gaussian decay [4,11,13,14,22,23] where the magnetic field parameter is sufficiently different initially from the one used during the evolution. We will derive out the analytical expression for the width of the Gaussian as a function of parameters of the initial state and numerically verify the expression. We will also explain the origin of the so-called universal regime of the Gaussian decay in the strong coupling regime [4,13].

The dynamical evolution of the reduced density matrix can be used to describe the decoherence process. For a two-level qubit system such as a central spin, which is coupled to the environment, the coefficients of the off-diagonal terms in the reduced density matrix of the system, named as "coherence factor" in the following discussion in this paper, may describe the degree of the decoherence. It was found that in such a simple model and with a few additional generic assumptions, the coherence factor evolutes as Gaussian decay with time. So the Gaussian decay is general and important for the decoherence research.

The paper is organized as follows. In the next section we introduce the model Hamiltonian and the way through which we describe the decoherence of the system and the initial states of the environment. In Section 3, we choose the ground state of the initial Hamiltonian as the initial state of the environment in weak coupling. In this section we discuss the revivals, critical behavior and Gaussian decay in the decoherence process. In Section 4, we choose thermal equilibrium state as initial state and analyze the dependence of the decay speed on the temperature T. In Section 5, we analyze the decoherence process in strong coupling and discuss the Gaussian envelope. Finally, in Section 6 we draw our conclusions.

2. The model

Now we introduce the Hamiltonian and the model. In this paper, we consider a two-level quantum system (central spin) transversely coupled to an environment which is described by one-dimensional XY spin chain model. The total Hamiltonian is given by $H = H_E^{\lambda} + H_I$, where (we take $\hbar = 1$ in this paper)

$$H_E^{\lambda} = -J \sum_{l=1}^{N} \left(\frac{1+\gamma}{2} \sigma_l^x \sigma_{l+1}^x + \frac{1-\gamma}{2} \sigma_l^y \sigma_{l+1}^y + \lambda \sigma_l^z \right), \quad (1)$$

$$H_I = -Jg\sigma^z \sum_{l=1}^{N} \sigma_l^z .$$

Here H_E^{λ} denotes the Hamiltonian of the environmental spin chain and H_I denotes the interaction between the central spin and the environment. σ^{α} $(\alpha = x, y, z)$ and σ_l^{α} are the Pauli matrices used to describe the central spin and the lth spin of the spin chain, respectively. The parameters J and λ characterize the strengths of the Ising interaction and the intensity of the magnetic field applied along the z axis, and γ measures the anisotropy in the in-plane interaction. N is the total site number