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Annals of Physics 317 (2005) 72–106

ANNALS
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PHYSICS

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Decoherence in strongly coupled quantum oscillators

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Received 12 July 2004; accepted 20 December 2004

Abstract

In this paper, we present a comprehensive analysis of the coherence phenomenon of two coupled dissipative oscillators. The action of a classical driving field on one of the oscillators is also analyzed. Master equations are derived for both regimes of weakly and strongly interacting oscillators from which interesting results arise concerning the coherence properties of the joint and the reduced system states. The strong coupling regime is required to achieve a large frequency shift of the oscillator normal modes, making it possible to explore the whole profile of the spectral density of the reservoirs. We show how the decoherence process may be controlled by shifting the normal mode frequencies to regions of small spectral density of the reservoirs. Different spectral densities of the reservoirs are considered and their effects on the decoherence process are analyzed. For oscillators with different damping rates, we show that the worse-quality system is improved and vice versa, a result which could be useful for quantum state protection. State recurrence and swap dynamics are analyzed as well as their roles in delaying the decoherence process.

PACS: 42.50.Ct; 42.50.Dv; 03.65.Bz; 32.80.−t

Keywords: Decoherence; Entanglement; Dissipation; Quantum network

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doi:10.1016/j.aop.2004.12.007

1. Introduction

The process of decoherence of quantum states has long been a central issue in the description of quantum measurements [1–3]. In recent years, experimental advances in the domain of cavity QED and trapped ions have allowed the decoherence of photon [4] and phonon [5] field states to be probed in more depth, providing insights into the borderline between the classical and quantum descriptions of the physical world. The decoherence time of a superposition of coherent states in a cavity field was measured [4] and shown to be in full agreement with theoretical predictions [6,7]. In trapped ions systems, the observed damping of Rabi oscillations has motivated a number of articles on the main sources of noise leading to decoherence [8–11]. Such experimental achievements in matter–field interactions have also encouraged a deep dialog between theoretical and experimental physics, resulting in a degree of mastery of fundamental quantum phenomena that may herald a new stage in the technology of communication [12] and computation [13].

The exploration of the borderline between quantum and classical descriptions of nature [2] has impelled the generation of superposition states of mesoscopic systems, known as "Schrödinger cat states" [4,5]. Such superpositions are irreversibly affected by their surroundings, whose effect is to destroy probability interference (coherence), and continuously transformed into statistical mixtures. Thus, the environment plays a key role in the establishment of a direct correspondence between quantum and classical dynamics. While the decoherence time of a superposition state depends on the amplitude of the field, the relaxation does not, since the model adopted for the relaxation process is amplitude damping, achieved by coupling the systems bilinearly to the degrees of freedom of the reservoir.

Decoherence and its dependence upon the amplitude of the superposition state is the main obstacle to the implementation of a logic network based on quantum gates [14,15]. The dream of quantum communication and computation comes up against the nightmare of decoherence mechanisms [16], owing not only to the inevitable action of the surrounding environment but also to the intrinsic fluctuations in the interaction parameters required for logic operations [8–10]. The need for huge superpositions of qubit states in the practical implementation of logical operations imposes the requirements that the quantum systems be almost totally isolated from the environment and that the interaction parameters involved be tightly controlled. For this reason, investigation of the sources of noise in such promising quantum systems is a crucial step towards the realization of a quantum logic processor. There is also a major effort being made in present-day research, to discover mechanisms to prevent decoherence occurring in actual physical systems, by using parity kicks [17], stroboscopic feedback [18], engineered driving fields [19] or an engineered reservoir [20–22]. Moreover, quantum error correcting codes have been given which protect quantum information from any error, including gating errors, provided the error rates are below a certain threshold [23,14]. An overview of quantum error prevention strategies and a discussion of the combinations of these strategies which have recently been proposed in the literature is presented in [24]. In this light, the main concern of the present work is to analyze the