Highly nonclassical quantum states and environment induced decoherence

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1 Preliminaries and scientific objectives

Preliminaries

The relation between quantum and classical mechanics is a question of interest since the foundation of quantum theory. The notion of decoherence is related to the experience that in the macroscopic world we do not observe any sign of the superposition principle, which is fundamental in quantum mechanics. This contrast is the most striking when – following the famous *gedanken experiment* of Schrödinger [1,2] – we consider the superposition of states that are well-distinguishable and have a clear classical interpretation, like a dead and living cat. These highly nonclassical, so-called Schrödinger-cat states are allowed in quantum mechanics, but due to the lack of the superposition principle, they are not present in a classical world.

The theory of environment induced decoherence has been developed since the 1970s, and it is based on the assumption, that quantum mechanics is universally valid, it can describe not only particles but macroscopic bodies as well [3,4]. The fundamental question naturally arising is that in a system that is governed by the rules of quantum mechanics, how it is possible to explain the emergence of classical properties. Nowadays the

most accepted answer emphasizes that no (quantum) systems can be perfectly isolated; they are always coupled to the environment. This coupling can be weak, but it is always present and modifies the dynamics of the system under investigation. The state of the system and the environment predominantly become entangled, rendering it impossible to assign a quantum mechanical pure state to either party. From this point of view, the dynamical process of decoherence is the delocalization of the local, typically nonclassical system states. The formation of entanglement, i.e., the delocalization, presents itself locally (when only the system is investigated) as the disappearance of the nonclassical quantum states.

Knowing the interaction between a quantum system and its environment, it is possible to determine the system states that are the most robust against the effects of the environment. In well-known models these stable states have the property that they can be interpreted in classical terms. On the contrary, their superpositions have a very short lifetime, thus the result of the decoherence will be a classical mixture of the stable states. The determination of these states is therefore essential when our aim is to investigate the direction of decoherence, that is, to calculate the mixture into which decoherence drives the system.

Due to the fast development in the experimental techniques, nowadays it is possible to investigate the dynamics of decoherence also in laboratories. Rydberg atoms traversing a cavity [5], entangled photon pairs [6], or a single ion in a Paul trap [7] can shed new light on long-lived theoretical questions. Besides its fundamental importance, understanding the mechanisms that lead to the disappearance of quantum superpositions can have practical applications as well. The recently born and rapidly developing field of quantum information technology relies on the quantum nature of the physical objects that store, carry and process information. This is the very origin of the classically unreachable computational power of quantum algorithms [8]. If the decoherence destroys quantum interferences between the states of these objects, they cease to be useful components of a quantum computer. Therefore it can be essential to use so-called decoherence-free states, that are stable against the effects of the environment and, additionally, their superpositions are also keep their quantum properties long enough to implement a quantum algorithm.

Scientific objectives

Decoherence is, first of all, a fundamental problem, but exploring its mechanisms in well defined model systems can lead to practical results as well. This motivated us to investigate concrete quantum systems in the framework if the environment induced decoherence. One of the chosen physical systems is a diatomic molecule, where the potential energy of the nuclei is an anharmonic function of their distance. A system of two-level atoms [9], which can be important from the viewpoint of quantum information technology, is also to be investigated. Compared to pure numerical results, knowing the direction of the decoherence provides more insight into the dynamics in the case of both systems. We plan to determine the characteristic time of the decoherence, and find states that can keep their quantum properties for the longest possible time. Additionally, we intend to investigate the relation between decoherence and dissipation, as usually the latter phenomenon also takes place in an open quantum system. Using these experiences, we would like to propose a scheme that can prepare decoherence-free states using the experimental techniques presently available.

2. Scientific methods

Our investigations are based on the methods that are developed to describe a quantum system being in interaction with its environment. In order to be able to concentrate on the system of interest, we have to average over the possible states of the environment. We consider the situation when the characteristic time of the relaxation in the environment is much shorter than the time scales related to the internal dynamics of the system. In this Markovian case one can obtain a differential equation termed as master equation that involves only system degrees of freedom [10,11]. The stability of different initial states can be estimated by analytical short-time calculations. The density operator of the system at an arbitrary time instant is obtained by solving the master equation numerically. The entropy of the system helps us investigate the formation of system-environment entanglement. The Wigner function [12,13] of the system visualizes the process of the decoherence in an instructive way, and additionally, it can be used to analyze the disappearance of the degree of nonclassicality as a function of time [14].

3. New results

1. We have shown that decoherence and dissipation are two processes that can be distinguished dynamically in a system of two-level atoms as well as in the case of a vibrating diatomic molecule. We have described a method that is valid in both systems and can determine the characteristic time of the decoherence.

2. We have obtained a new master equation for a general anharmonic system, taking into account that the rate of the environment induced transitions depends on the involved Bohr frequencies, which are generally different for different transitions.

3. We have demonstrated that the decoherence of molecular wave packets in an anharmonic potential follows a general scheme: The result of the decoherence can be interpreted as a mixture of states localized along the phase space orbit of the corresponding classical particle, independently from the initial state.

4. We have applied the method of point 1 to the case of different molecular wave packets, and we have shown that the characteristic time of the decoherence decreases when the amplitude of the oscillations increases.

5. Using the method of point 1, we have shown that in a system of two-level atoms certain superpositions of atomic coherent states, the so-called symmetric Schrödinger-cat states, exhibit exceptionally slow decoherence.

6. We have described the direction of the decoherence in a system of two-level atoms so that our scheme is valid also in the case of the slowly decohering symmetric Schrödinger-cat states.

7. We have proposed a method that can prepare decoherence-free, subradiant states in a cavity. We have analyzed the proposed method and have shown that it is feasible with presently available experimental setups.

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Publications

The thesis is based on the following publications:

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