Results in Physics 8 (2018) 89–92

Contents lists available at ScienceDirect

Results in Physics

journal homepage: www.journals.elsevier.com/results-in-physics

Quantum transfer energy in the framework of time-dependent dipole-dipole interaction

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A R T I C L E I N F O

Article history:
Received 28 July 2017
Received in revised form 30 October 2017
Accepted 3 November 2017

Keywords:
Quantum energy transfer
Quantum acceleration and speed
Dipole-dipole interaction
Population
Dimer system
Two-level atom system
Quantum correlations

A B S T R A C T

In this work, we examine the process of the quantum transfer of energy considering time-dependent dipole-dipole interaction in a dimer system characterized by two-level atom systems. By taking into account the effect of the acceleration and speed of the atoms in the dimer coupling, we demonstrate that the improvement of the probability for a single-excitation transfer energy extremely benefits from the incorporation of atomic motion effectiveness and the energy detuning. We explore the relevance between the population and entanglement during the time-evolution and show that this kind of nonlocal correlation may be generated during the process of the transfer of energy. Our work may provide optimal conditions to implement realistic experimental scenario in the transfer of the quantum energy.

Introduction

The absorption of light energy by an atom is typically followed by its electronic transition from the ground state to the excited state. This electronic energy relocated to another nearby atom by a process known as resonance energy transfer. The most favoring spectral features for better capture of solar light and efficient resonance energy transfer occur when the spectral and spatial cross section in a photosynthetic light-harvesting system is high [1–7]. The quantum transfer of energy between a donor atom (the one that gets excited) to an acceptor atom is usually described by an incoherent process. In this context, the energy transfer with the impact of inter-atomic interaction in the framework of dipole-dipole coupling is described using electronic coupling elements. Coherent energy transfer, however, is considered as an interesting period of photosynthesis, by which excitation energy get transferred efficiently from the photosensitizers (pigments) to the reaction center as recently reported [8–14]. In general, the transfer of energy via a network of pigments is a very complicated process. To have an idea about the mechanism of light harvesting complex, a simple model representing the light harvesting complex based on a dimer system consists of a donor (the one excited) and an acceptor (the one photosensitized) is proposed. A number of both theoretical and experimental studies have been recently investigated using the coherence in the transport of the quantum energy [15,16]. Studies in multichromophoric quantum systems indicated that exciton delocalization together with pure dephasing has been considered as effective parameters in improving the efficiency of quantum transfer [17,18]. On the other hand, the correlations introduced by a bath in different site energies are shown to affect the dephasing noise.

Recently, some experiments have been revealed the existence of quantum processes that enjoy the coherence alive for a long time in space ranges [19]. Especially, within the photosynthetic processes in light-harvesting complex processes, a typical oscillatory dynamics can include the quantum coherence. The result obtained clarified that in the quantum systems of photosynthetic

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https://doi.org/10.1016/j.rinp.2017.11.003
2211-3797/

antenna the correlation may be eliminated in the dynamic processes. The longest living of the quantum coherence alone, however, will not be suitable to get a high efficiency of quantum energy transfer. Furthermore, the quantum coherence provides an essential role in controlling the dynamical properties of a system dynamics, considering dissipative and phase damping, and its populations of excitation in a given quantum state.

As known that the entanglement is one of the most promising phenomena in quantum technology, which proposed the nonlocal correlations between different physical systems [20–28]. In this way the investigation of entanglement as the main type of quantum correlation and its outcomes of quantum measurements led to understand and solve different physical problems [29,30]. More recently, the development of quantum information processing (QIP) has been provided rise to a large knowledge and also augmented the literature of entanglement phenomenon, which has performed the optimal tasks of QIP and quantum metrology [31–37]. The significance of entanglement in different applications has led to analysis and investigation of high-dimensional quantum systems and bring the new role of this kind of correlation in many-particle quantum systems [38].

Understanding the very fundamental mechanism responsible for high-efficiency energy transfer in photosynthesis is expected to lead to both fundamental and practical implications. Our results reported recently on a single-excitation energy transfer have shown that the enhancement probability for this process benefits well from the photon-number transition, energy detuning, classicality of the field and time-dependent coupling effect for a dimer system displayed by two-level systems (TLSs) interacting with a cavity field [39]. In this paper, a model that almost describes a realistic experimental scenario based on an atom-atom interaction will be adapted to study the acceleration and speed effects in the interaction between the pigments. We consider the coupling term as a sinusoidal function of a second degree of the time. In a single excitation from a donor to an acceptor where each one is modeled by a TLS, the coupling effect, and energy frequencies, which might affect the efficiency of the coherent energy transfer will be explored in details. This form of the coupling term could include the acceleration and speed effects of the TLSs on the physical quantities during the process of the energy transfer. Additionally, the dynamical behavior of the entanglement of the pigment states through the energy transfer process will be investigated.

This paper is structured as follows. In Section 'Model of the physical system', we present the formalism that describes the model of the quantum transfer energy in the framework of time-dependent dipole-dipole interaction and showing the dependence of the physical parameters on the population dynamics for a single-excitation and entanglement in the dimer system. In Section 'Result and discussions', we present the numerical results and explain the physical phenomena that can be observed in the framework of the atomic motion. Finally, some conclusions are given in Section 'Conclusion'.

Model of the physical system

Thus, a dimer system with its dipole-dipole interaction and time-dependent coupling effect is the undertaken physical system.

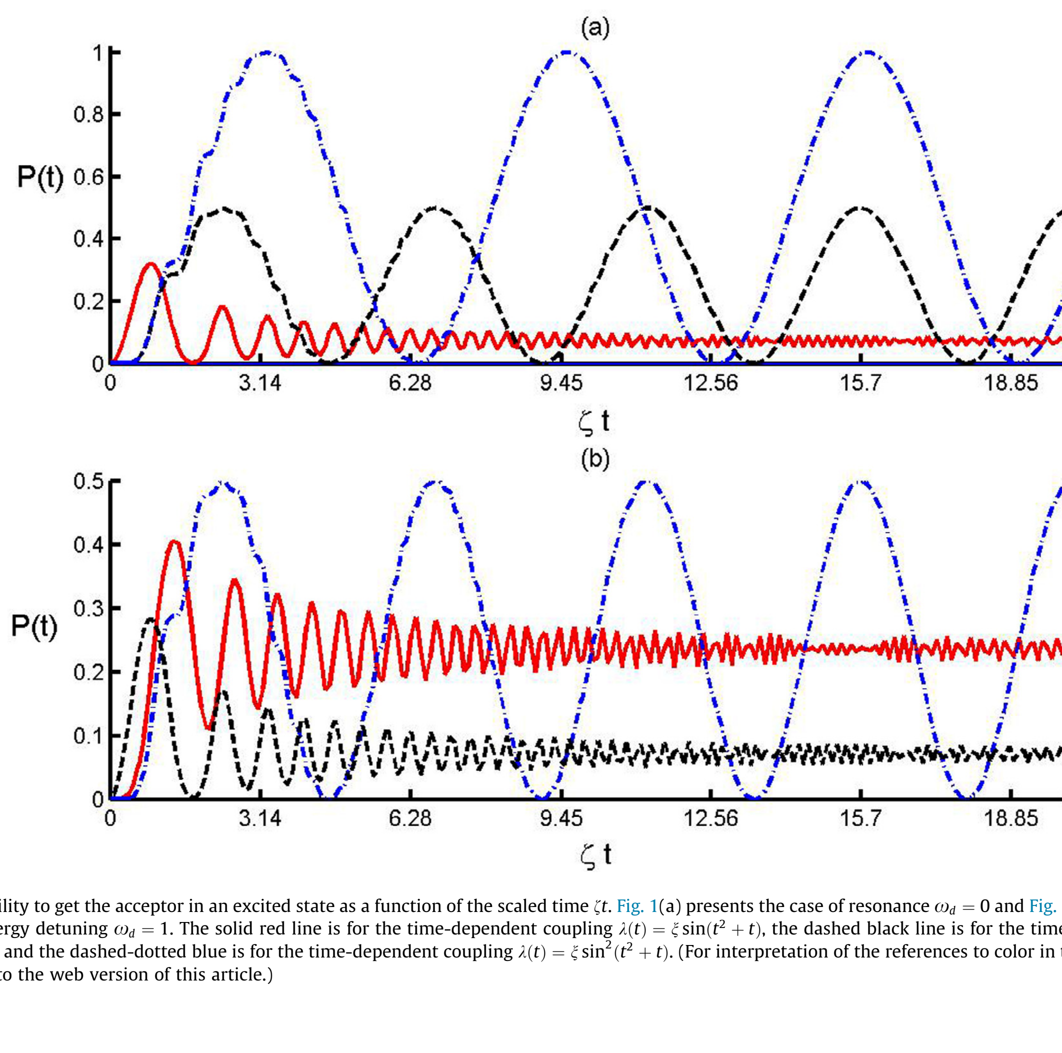

Fig. 1. The probability to get the acceptor in an excited state as a function of the scaled time ζt. Fig. 1(a) presents the case of resonance $\omega_d = 0$ and Fig. 1(b) is corresponds to the case of the energy detuning $\omega_d = 1$. The solid red line is for the time-dependent coupling $\lambda(t) = \xi \sin(t^2 + t)$, the dashed black line is for the time-dependent coupling $\lambda(t) = \xi \cos(t^2 + t)$, and the dashed-dotted blue is for the time-dependent coupling $\lambda(t) = \xi \sin^2(t^2 + t)$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)