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Nonequilibrium steady state transport of collective-qubit system in strong coupling regime

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ABSTRACT

We investigate the steady state photon transport in a nonequilibrium collective-qubit model. By adopting the noninteracting blip approximation, which is applicable in the strong photon–qubit coupling regime, we describe the essential contribution of indirect qubit–qubit interaction to the population distribution, mediated by the photonic baths. The linear relations of both the optimal flux and noise power with the qubits system size are obtained. Moreover, the inversed power-law style for the finite-size scaling of the optimal photon–qubit coupling strength is exhibited, which is proposed to be universal.

1. Introduction

Deep understanding and optimal control of quantum propagationin low-dimensional light-qubit (atom) hybrid systems are of fundamental interest and practical importance [1]. Particularly, the collective effect on the information and energy transport due to light-qubit (atom) scattering, as a novel measuring feature, has recently attracted dramatic attention [2–5]. Many works have been carried out to observe such effect, ranging from solid state physics [6,7], quantum biology [8], to quantum optics [9,10]. The transport scheme, quantum flow from hot source to cold drain, can be typically established by applying the thermodynamic (e.g., temperature) bias, in accordance with the second law of thermodynamics.

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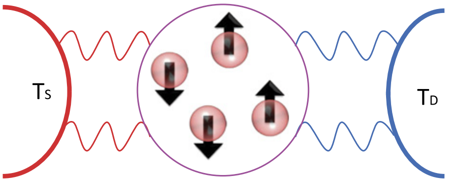

Fig. 1. (Color online) Schematic description of nonequilibrium qubits system: the left red arch and right blue arch represent the source and drain photonic baths, with the temperature given by T_S and T_D, respectively; the central pink circles combined with the arrows describe the two-level qubits; the curved red and blue lines describe the system–bath interaction.

The prototype paradigm of collective-qubit systems to characterize quantum transport based on photon–qubit interaction is termed as Dicke model. It was originally pointed out by R.H. Dicke, who described N identical two-level atoms coupled to single radiation field mode [11]. Dicke model has been extensively studied in quantum superradiant phase transition associated with collective self-organization of atoms, which predicts the universal finite-size scaling effect [12,13]. Moreover, the influence of photon dissipation on the collective-qubit model is analyzed by considering continuous radiation modes. The anomalous superradiant-like relaxation, dynamical quantum beat and quantum phase transition have been unraveled, which significantly differ from the counterpart in spin-boson model ($N = 1$) [14–17].

Recently, steady state transport behavior of collective qubits weakly coupled to two photonic baths is studied together within Redfield scheme and full counting statistics [18,19], where the thermodynamic bias is applied to drive the unidirectional photonic flow [20,21]. The influence of bath temperatures on the generation of collective quantum transport is intensively analyzed. As is known in nonequilibrium spin-boson model, strong system–bath coupling plays nontrivial role to exhibit nonmonotonic flux behaviors by including the nonadditive and nonresonant transport processes between qubits and bosonic (e.g., phonon) baths [22–26]. Hence, it is indeed desirable to study the effect of strong photon–qubit interaction on quantum transport in collective-qubit system.

We adopt the nonequilibrium noninteracting-blip approximation (NIBA) [23,25,27–29] to study the steady state collective transport behaviors of multi-qubits system in strong coupling regime. It should be noted that, NIBA was originally developed by A.J. Leggett et al. and H. Dekker for the single-bath spin-boson model [22,30]. Recent works have extended the NIBA to nonequilibrium problems [23,25,27–29], where the Marcus limit [31] is usually introduced for heat transport and the heat current expression. In the present work, the indirect qubit–qubit interaction mediated by photonic baths is clearly revealed, contributing to collective behaviors. Then, the effect of strong photon–qubit coupling on photonic energy current fluctuations (e.g., flux, noise power) is investigated, and the finite-size scaling of the corresponding optimal observables is discussed. This paper is organized as follows: in Section 2, we describe the collective-qubit model and derive the quantum kinetic equation in collective-angular momentum basis. The comparison of steady state population in strong coupling regime is made with the counterpart within Redfield scheme. In Section 3, the full counting statistics of photonic energy flux is established, and the finite-size scaling of the current fluctuations is analyzed. A concise summary is given in the final section.

2. Nonequilibrium collective-qubit system

2.1. Model

The nonequilibrium collective-qubit model at Fig. 1, composed by N identical two-level qubits interacting with two photonic baths, is described by

$$\hat{H} = -\frac{\epsilon_0}{2}\sum_{n=1}^{N}\hat{\sigma}_z^n + \frac{\Delta}{2}\sum_{n=1}^{N}\hat{\sigma}_x^n + \sum_{n=1}^{N}\sum_{v,k}\lambda_{v,k}^n\hat{\sigma}_z^n(\hat{b}_{k,v}^\dagger + \hat{b}_{k,v}) + \sum_{k,v}\omega_k\hat{b}_{k,v}^\dagger\hat{b}_{k,v}, \tag{1}$$