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# Resonance fluorescence of strongly driven two-level system coupled to multiple dissipative reservoirs

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We present a theoretical formalism for resonance fluorescence radiating from a two-level system (TLS) driven by any periodic driving and coupled to multiple reservoirs. The formalism is derived analytically based on the combination of Floquet theory and Born–Markov master equation. The formalism allows us to calculate the spectrum when the Floquet states and quasienergies are analytically or numerically solved for simple or complicated driving fields. We can systematically explore the spectral features by implementing the present formalism. To exemplify this theory, we apply the unified formalism to comprehensively study a generic model that a harmonically driven TLS is simultaneously coupled to a radiative reservoir and a dephasing reservoir. We demonstrate that the significant features of the fluorescence spectra, the driving-induced asymmetry and the dephasing-induced asymmetry, can be attributed to the violation of detailed balance condition, and explained in terms of the driving-related transition quantities between Floquet-states and their steady populations. In addition, we find the distinguished features of the fluorescence spectra under the biharmonic and multiharmonic driving fields in contrast with that of the harmonic driving case. In the case of the biharmonic driving, we find that the spectra are significantly different from the result of the RWA under the multiple resonance conditions. By the three concrete applications, we

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illustrate that the present formalism provides a routine tool for comprehensively exploring the fluorescence spectrum of periodically strongly driven TLSs.



## 1. Introduction

In recent years, the resonance fluorescence has attracted widespread attentions both in experiment and theory [1–18], which is not only motivated by testing fundamental quantum optics theory but also for the purposes of developing single quantum emitters for quantum light spectroscopy and quantum information applications. In general, the spectrum of the fluorescence light is of primary interest, which can be calculated in theory and measured in experiment. It is well known that the fluorescence spectrum consists of coherent and incoherent components. The coherent one results from the elastic scattering while the incoherent one from the inelastic scattering [1]. In particular, in the case of a two-level system (TLS) driven by the monochromatic driving, the incoherent part is made up of three split peaks, known as Mollow triplet. The generation of Mollow triplet can be understood physically by using the so-called dressed atom model [19], which combines the TLS and the driving field. Within this model, the Mollow triplet is simply interpreted as a result of the transitions between the specific dressed states.

As resonance fluorescence in versatile experimental conditions are explored, the theory about radiation from the TLS has been intensively investigated and developed in two main ways. One is concerning with elaborated driving field other than the monochromatic one, for instance, optical pulse [14] and polychromatic driving field [18,20,21], etc. In these cases, the problem becomes complicated due to the applied driving field. The other involves different kinds of reservoirs and the simple monochromatic driving. It focuses the influence of the reservoirs coupled to the TLS on the spectral properties, such as dephasing coupling [15,16] and the narrowband vacuum [2,22], etc. To our knowledge, there is no general theoretical formalism to simultaneously reveal effects of both the arbitrary driving and the multiple reservoirs on the resonance fluorescence. In this work, we present a theoretical formalism that provides a unified treatment of resonance fluorescence spectrum of the TLS driven by an arbitrary periodic driving and coupled to multiple reservoirs. The interesting physics beyond the rotating-wave approximation (RWA) has been extensively studied both in experiment and theory. In particular, the strong periodic driving is experimentally accessible in the superconducting circuits that simulate the natural atoms. In such systems, it has been reported that the phenomena associated with the strong harmonic driving cannot be described by the RWA [23–25].

As is well known, we can solve the time evolution of the periodically driven TLS by the Floquet theory in the absence of the reservoirs [26–28]. On the other hand, provided that a TLS interacts weakly with the reservoirs, we can apply the Born–Markov master-equation approach to get the reduced dynamics of the TLS [29]. In the presence of the periodic driving and reservoirs, it is feasible to combine the Floquet theory and the Born–Markov master equation into the Floquet–Born–Markov (FBM) master equation [28,30,31]. It is noticeable that, in Ref. [32], the authors show that the FBM master equation is consistent with the second law of thermodynamics under strong driving conditions in which case the traditional quantum optical master equation becomes inapplicable and is inconsistent with the second law [33]. Intuitively, we can conclude that the FBM master equation provides the basis of unified treatment of fluorescence spectrum in the cases of periodic strong driving and multiple reservoirs.

In this paper, we present a formalism of fluorescence spectrum based on the FBM master equation, which is applicable to the situation where the TLS is periodically driven and weakly coupled to multiple reservoirs. When the Floquet state of the driven TLS is solved by the numerical technique or analytical method, the formalism allows us to not only straightforward calculate the spectrum but also explore the spectral features with a simple selection rule. In Section 3, to exemplify the theory, we