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Autler–Townes triplet spectroscopy

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Abstract

We study the effects of quantum interference in the spontaneous emission spectrum of a four-level driven atomic system. We use three strong laser fields to drive the atom and a weak laser field to prepare the initial state of the atom. The atomic system exhibits Autler–Townes triplet in the spectrum. The single Lorentzian peak splits into triplet and their widths are controlled by the relative strengths of the laser fields.

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1. Introduction

The study of spontaneous emission in an atomic system in the presence of the driving field has been a subject of great interest since the early work of Autler and Townes [1]. They developed a method to calculate the effect of a strong oscillating field on two states of a quantum mechanical system which are connected by the matrix elements of the atomic dipole moment. The major efforts to study the effects of quantum interference phenomenon [2] on spontaneous emission in simple two-level [3–5] and three-level [6–12] atomic system have been carried out during the last few years. The spontaneous emission spectrum of a three-level atomic system exhibits two peaks when upper two levels of the atom are coupled to a strong coherent field and decay takes place from the intermediate level to the lower level. The appearance of the two peaks is due to the dynamic stark splitting of the atomic levels and the quantum interference phenomenon in the atomic system.

Besides studying quantum interference effects in these simple atomic systems a substantial attention has been given to investigate this phenomenon in multi-level atomic systems. It is observed that quantum interference is responsible for the quenching of some spectral lines in the spontaneous emission spectrum of a four-level driven atomic system [13]. However, the spontaneous emission spectrum can be controlled by the phase associated with the driving fields and the condition needed for the quenching effect can be avoided [14]. Keitel showed that an unbounded line narrowing in the spontaneous emission spectrum can be achieved simultaneously with the control of the corresponding intensity [15]. An experimentally feasible four-level atomic scheme has been proposed [16] for quenching of the spectral lines, where it is possible to minimize or maximize the population in the dressed states of the upper two closely spaced decaying levels depending upon the relative strengths of the driving fields. The minimization or maximization of the atomic population in the dressed states is due to quantum coherence effect induced by the laser fields in the emission spectrum.

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It is also observed that the effects of quantum coherence and interference in the Autler–Townes spectrum have two very important consequences in quantum optics, i.e., the direct measurement of the quantum state of the cavity radiation field [17–19] and immediate localization of the single atom within the optical wavelength domain [20–24].

In all these schemes, the atom is prepared in the excited state before the interaction with the strong coupling fields. This may be a situation that is difficult to realize experimentally. In this paper, we consider a more realistic scheme of four-level atomic system such that the atom is prepared in the excited state via a weak coherent field during interaction with the strong driving fields. We investigate the quantum coherence and interference effects and observe that two dark lines arise due to the quantum interference which split the spontaneous emission spectrum into three spectral components. We call this three peaks spectrum as the Autler–Townes triplet. The presence of the two dark lines changes the shape of the spontaneous emission spectrum and also modifies the linewidth of the spectral components which depends on the relative strengths of the coherent driving fields. We consider various scenarios to study the effects of the coherence and decoherence processes in the spontaneous emission spectrum.

2. Model and equation

We consider a system in which atom interacts with strong driving fields in two different configurations, i.e., upper three-level coupling case and lower three-levels coupling case. In the first case, upper three-levels and in the second case, the lower three-levels of the atom are coupled to each other via three coherent driving fields. In both cases another weak coherent field is applied for pumping mechanism which couples the ground and upper excited state. In this way, the atom is prepared in its excited state during the evolution of the atomic system. Further, we consider the presence of all possible decay channels in order to study the decoherence effects in the atomic system.

2.1. Upper three-level coupling

In the upper three-level coupling configuration, we consider that the dipole allowed transitions $|b\rangle \rightarrow |c\rangle$ and $|a\rangle \rightarrow |c\rangle$ are coupled with two classical fields having Rabi frequencies Ω_2 and Ω_3, while the dipole forbidden transition $|a\rangle \rightarrow |b\rangle$ is induced by applying a strong magnetic field for a magnetic dipole allowed transition. We denote the Rabi frequency of this field by Ω_1. We also consider that the atom which is initially in the energy level $|d\rangle$ is excited to the level $|a\rangle$ via a weak pumping field having a Rabi frequency Ω_0 when it enters the interaction region, see Fig. 1a. The interaction Hamiltonian (in the rotating wave approximations) for this system is given by

$$\mathscr{V}^U(t) = (\Omega_1|a\rangle\langle b|e^{i\Delta_1 t} + \Omega_1^*|b\rangle\langle a|e^{-i\Delta_1 t}) + (\Omega_2|b\rangle\langle c|e^{i\Delta_2 t} + \Omega_2^*|c\rangle\langle b|e^{-i\Delta_2 t}) + (\Omega_3|a\rangle\langle c|e^{i\Delta_3 t} + \Omega_3^*|c\rangle\langle a|e^{-i\Delta_3 t}) + (\Omega_0|a\rangle\langle d|e^{i\Delta_0 t} + \Omega_0^*|d\rangle\langle a|e^{-i\Delta_0 t}), \quad (1)$$

where, $\Delta_1 = \omega_{ab} - \omega_1$, $\Delta_2 = \omega_{bc} - \omega_2$, $\Delta_3 = \omega_{ac} - \omega_3$ and $\Delta_0 = \omega_{ad} - \omega_0$. Due to the complexity involved in the computation of such atom-field system, we follow the master-equation approach to deal with the evolution of the atomic system. Hence the rate equation for the system is given by

$$\frac{\partial\rho}{\partial t} = -i[\mathscr{V}^U(t), \rho] + \Lambda\rho, \quad (2)$$

where $\mathscr{V}^U(t)$ represents the driving part of the atom-field system while $\Lambda\rho$ is the damping part [25]. The equations of motion for the matrix elements are obtained as

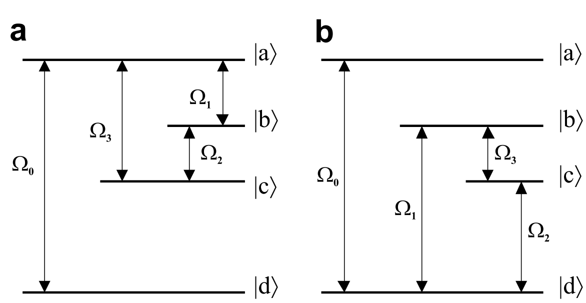

Fig. 1. Schematic of the atomic system (a) Upper-level coupling case and (b) Lower-level coupling case.