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Spectral line narrowing via spontaneously generated coherence in quantum dot molecules

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ABSTRACT

We theoretically demonstrate that it is possible to simulate spontaneously generated coherence in an asymmetric double quantum dot system, a quantum dot molecule. With the tunneling coupling, the system emulates to large degree a three-level system with quantum interference and the fluorescence spectrum can display ultranarrow lines. In our system the coupling field is not necessary and the degree of quantum interference can be controlled. The dressed states for this system are identified, and the spectral features are interpreted in terms of transitions among these dressed states. The system studied here is more practical and can permit the observation of spontaneously generated coherence without the need for closely lying levels and parallel dipole moments.

1. Introduction

The quantum interference between the decay channels, which is called spontaneously generated coherence (SGC), can lead to many phenomena, such as narrowing and quenching of spontaneous emission [1–3], amplification without inversion [4,5], transparency of a short laser pulse [6,7], and steady-state entanglement [8]. Apart from the interest of fundamentals, SGC can also find applications in many fields such as quantum information and computation [9], all-optical switching [10], quantum photocell [11] and high-precision metrology [12].

Note, however, that SGC only exists in such atoms having closely lying levels and that corresponding dipole matrix elements are not orthogonal. That is, the closely lying levels should have the same J and mJ quantum numbers [13]. However, the rigorous conditions of near-degenerated levels and nonorthogonal dipole moments are rarely met in real atoms so no experiment has been carried out in atoms to observe the SGC effect directly.

However, the type of quantum interference results from the incoherent decay processes can be realized in other systems. Modified vacuum, such as cavity field [14], anisotropy vacuum [15], photonic crystals [16] and left-handed materials [17] can lead to quantum interference among the decay channels with orthogonal dipole moment. The SGC effect can be also simulated with atoms in the dressed-state picture [18,19]. And most recently, we have observed SGC on absorption and fluorescence in rubidium atomic beam via the coherent laser field experimentally [20–22]. But all of these works have to be done in atomic vapor [23], atomic beam [20–22] or cold atom [24], so it is not convenient to realize SGC in such gas medium.

In semiconductor quantum dots, confined electrons and holes exhibit atom-like properties, which encouraged us to extend above studies to a solid system. Single quantum dots coherently driven by strong electromagnetic fields have been used to investigate quantum interference phenomena as electromagnetically induced transparency (EIT) [25], Autler-Townes splitting (ATS) and Mollow triplets [26,27]. Besides, single quantum dots can also be used in many fields such as all-optical quantum gate [28], ultralow-threshold laser [29] and quantum information [30].

Great progresses in the fabrication and physics of single quantum dots focus people's attention on quantum dot molecules (QDMs). Recently, the vertically coupled QDMs [31] and the laterally coupled QDMs [32] have been produced by molecule beam epitaxy. Quantum dots coupled by tunneling, are systems where it is possible to create Λ configurations. Many works have been carried out about this system, such as voltage controlled EIT and slow light [33–36], excitonic entanglement [37,38], protection of quantum states [39], controlled rotation of exciton qubits [40] and exciton-spin memory [41].

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In this paper, we investigate the spectrum of fluorescence in the QDMs system controlled by tunneling. With the tunneling coupling our system emulates to a large degree a V-type system with SGC, where ultrasharp spectral lines may be produced due to the SGC effect. Compared with the atomic system, the advantage of realizing SGC in QDMs is twofold. First, in atomic systems it is crucial to have at least one coupling laser field to create the necessary coherence [22–24]. However, in this paper we show that SGC can be simulated in QDMs by an external bias voltage, therefore requiring no auxiliary laser field. Second, the QDMs has widely adjustable parameters by accurately tailoring their shapes and sizes. For example, in this paper, we show that the degree of the SGC can be manipulated by changing the decay rate of indirect exciton of QDMs. However, such a property can hardly be found in the atomic medium. The QDMs scheme proposed here permits the observation of the interesting features predicted for three-level systems showing strong quantum interference, but without the need for near-degenerated levels and nonorthogonal dipole moments.

The remainder of this paper is organized as follows. In Section 2, The basic dynamics equations of motion, and their solution for the fluorescence spectrum are derived. In Section 3, we analyze our results and discuss in detail the influence of the tunneling and the decay rate of QDMs on the fluorescence spectrum. In Section 4, we explain the corresponding features with the transition properties of the dressed states generated by the tunneling. Section 5 contains a summary of the results.

2. Theory and model

Fig. 1(a) shows the V-type system with SGC. The atom consists of two excited levels $|+\rangle$ and $|-\rangle$ separated from the ground level $|0\rangle$ by transition frequencies ω_+ and ω_-, and connected by the electric dipole moments $\boldsymbol{\mu}_+$ and $\boldsymbol{\mu}_-$, respectively. We assume that the excited levels $|+\rangle$ and $|-\rangle$ can decay to the level $|0\rangle$ by spontaneous emission with the rate of γ_+ and γ_-, respectively, whereas direct spontaneous transitions between the excited sublevels are dipole forbidden. The Hamiltonian in the frame rotating with the laser frequency ω_L is of the form (we use units such that $\hbar=1$)

$$H=(\Delta_+-\omega_{+-})|-\rangle\langle-|+\Delta_+|+\rangle\langle+|+[(\Omega_-|-\rangle\langle0|+\Omega_+|+\rangle\langle0|)+H.c.], \tag{1}$$

where $\Omega_i(i=+,-)$ is the Rabi frequency of the laser field for the respective atomic transition, and ω_{+-} is the splitting of the sublevels and $\Delta_+=\omega_+-\omega_L$ is the detuning between the frequency ω_+ and the driving laser frequency.

Assuming that such an atomic system is damped by the standard vacuum, the master equation for the reduced density operator ρ of the atom in the rotating frame then takes the form

$$\begin{aligned}\dot{\rho}=&-i[\rho,H]+\frac{1}{2}\gamma_-(2|0\rangle\langle-|\rho|-\rangle\langle0|-|-\rangle\langle-|\rho-\rho|-\rangle\langle-|)\\&+\frac{1}{2}\gamma_+(2|0\rangle\langle+|\rho|+\rangle\langle0|-|+\rangle\langle+|\rho-\rho|+\rangle\langle+|)\\&+\frac{1}{2}\gamma_{-+}(2|0\rangle\langle-|\rho|+\rangle\langle0|-|+\rangle\langle-|\rho-\rho|+\rangle\langle-|)\\&+\frac{1}{2}\gamma_{+-}(2|0\rangle\langle+|\rho|+\rangle\langle0|-|-\rangle\langle+|\rho-\rho|-\rangle\langle+|),\end{aligned} \tag{2}$$

where $\gamma_{ij}=p\sqrt{\gamma_i\gamma_j}$, $(i\neq j=+,-)$represents the effect of quantum interference resulting from the cross coupling between the transitions $|+\rangle\to|0\rangle$ and $|-\rangle\to|0\rangle$. The parameter p characterizes the strength of the cross coupling which is crucially dependent on the angle (θ) between the two atomic transition electric dipole moments $\boldsymbol{\mu}_+$ and $\boldsymbol{\mu}_-$. Hence, the relation below holds $p=\cos\theta$. If $\boldsymbol{\mu}_+$ is parallel to $\boldsymbol{\mu}_-$, then $p=1$ and the interference is maximum, while if $\boldsymbol{\mu}_+$ is perpendicular to $\boldsymbol{\mu}_-$, then $p=0$ and the quantum interference disappears.

From Eq. (2) we can see that the spontaneous decay in this system is off diagonal, which indicate the equation of motion for the density matrix element ρ_{ij} will contain damping terms that are proportional to ρ_{kj} and/or ρ_{ik}, as well as the diagonal damping terms proportional to ρ_{ij}.

Through the method described in Ref [18], we transform to a set of new bases which are the following symmetric and antisymmetric superposition states of the excited levels:

$$|2\rangle=\frac{1}{\sqrt{\gamma_++\gamma_-}}(\sqrt{\gamma_-}|-\rangle+\sqrt{\gamma_+}|+\rangle), \tag{3a}$$

$$|1\rangle=\frac{1}{\sqrt{\gamma_++\gamma_-}}(\sqrt{\gamma_+}|-\rangle-\sqrt{\gamma_-}|+\rangle). \tag{3b}$$

For simplicity, we assume that $\gamma_+=\gamma_-=\gamma$, then the above equation is transformed to

$$|2\rangle=\frac{1}{\sqrt{2}}(|-\rangle+|+\rangle), \tag{4a}$$

$$|1\rangle=\frac{1}{\sqrt{2}}(|-\rangle-|+\rangle). \tag{4b}$$

In the basis of Eq. (4), the decay terms in Eq. (1) are diagonalized. And we also assume $\Omega_+=\Omega_-=\Omega$, then the Hamiltonian and master equation take the form:

$$H=\Delta(|1\rangle\langle1|+|2\rangle\langle2|)-\frac{1}{2}\omega_{+-}(|1\rangle\langle2|+|2\rangle\langle1|)+\sqrt{2}\Omega(|1\rangle\langle0|+|0\rangle\langle1|), \tag{5}$$

$$\begin{aligned}\dot{\rho}=&-i[\rho,H]+\frac{1}{2}\gamma(1+p)(2|0\rangle\langle1|\rho|1\rangle\langle0|-|1\rangle\langle1|\rho-\rho|1\rangle\langle1|)\\&-\frac{1}{2}\gamma(1-p)(2|0\rangle\langle2|\rho|2\rangle\langle0|-|2\rangle\langle2|\rho-\rho|2\rangle\langle2|),\end{aligned} \tag{6}$$

where $\Delta=\Delta_+-\frac{1}{2}\omega_{+-}$ This is an indication that the laser field couples only to the symmetric state and the excited state decays

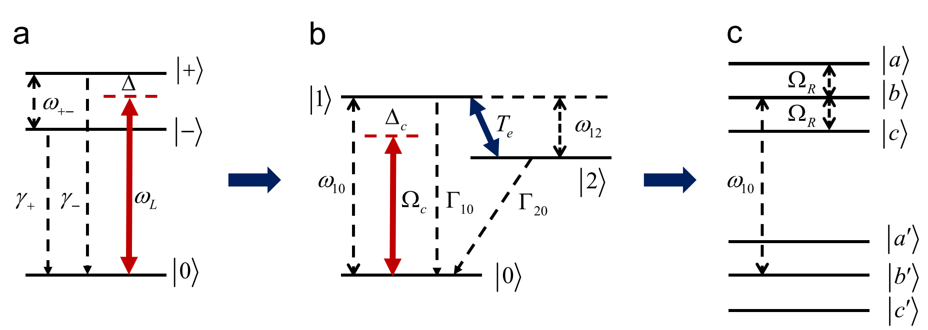

Fig. 1. (a) Energy-level scheme of a three-level atomic system in the V configuration with SGC and (b) schematic band structure and level configuration of a double QD system. (c) The dressed states of a double QD system under the laser field and the tunneling.