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Cavity quantum electrodynamics with quantum interference in a three-level atomic system

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ABSTRACT

Spontaneously generated coherence and enhanced dispersion in a V-type, three-level atomic system interacting with a single mode field can considerably reduce the radiative and cavity decay rates. This may eliminate the use of high finesse, miniaturized cavities in optical cavity quantum electrodynamics experiments under strong atom-field coupling conditions.

1. Introduction

In experiments related to cavity quantum electrodynamics (QED), it is required to deal with three important parameters governing the atom-field dynamics, which are the atom-field coupling strength g, the radiative decay rate of the atom γ_a, and the cavity decay rate γ_{cav}. The parameter g characterizes the oscillatory exchange of excitation between the atom and the cavity field mode while its magnitude relative to the parameters γ_a and γ_{cav} decides if the coupling between atom and resonator is weak or strong. Both the suppression and enhancement of radiative decay rate γ_a have been observed in cavities subtending a very large solid angle over the atom under the weak coupling regime $\gamma_a \ll g^2/\gamma_{cav} \ll \gamma_{cav}$, which is in good agreement with the perturbation theory [1–4]. The strong coupling regime has also been successfully realized with Rydberg atoms in the microwave domain where the condition $g^2/\gamma_{cav} \gg \gamma_{cav} > \gamma_a$ is readily met and the Rydberg atoms possess very large dipole moments, long radiative decay times (using circular Rydberg states), and a superconducting cavity operating at 10 K is employed [5]. For cavity QED experiments in the optical domain, the strong coupling regime is usually very difficult to achieve since the coupling parameter g is intrinsically weak in comparison to γ_a and γ_{cav}. One can express the coupling parameter as $g = (\mu^2\omega_0/2\hbar\epsilon_0 V)^{1/2}$, where μ is the transition dipole moment and V is the effective cavity mode volume. Since the magnitude of g is small in the optical domain, one needs to greatly reduce V to achieve the strong coupling regime [6,7]. Alternatively, one can define the critical photon number $m_0 = \gamma_a^2/2g^2$ and the critical atom number $N_0 = 2\gamma_a\gamma_{cav}/g^2$ to do nonlinear optics with one photon per mode and single-atom switching for optical cavity response. In these cases, the parameter g (internal interaction strength) is responsible for the information exchange while γ_a and γ_{cav} (external dephasing/dissipative rates) are responsible for the rate of information loss from the system. For strong coupling regimes, it is required to have $m_0 \ll 1$ and $N_0 \ll 1$. This implies that the mode volume should be as small as possible and the photon leakage rate (γ_{cav}) should also be small, meaning that a very high-Q cavity with very large finesse is required. Various scaling configurations such as the *hourglass cavity* has been employed for this purpose. The record finesse of 3×10^6 has been achieved with $m_0 = 8 \times 10^{-6}$ and $N_0 = 7 \times 10^{-4}$; and $g = 110$ MHz, $\gamma_a = 2.6$ MHz, $\gamma_{cav} = 14.2$ MHz are reported for the cavity QED experiments with Cs atomic beams [8,9].

In this work, we propose an alternative way to reach the strong coupling regime in the optical domain for cavity QED experiments using the spontaneously generated coherence (SGC) in a three-level atom (V-type) to reduce the radiative decay rate (γ_a) [10,11]. The reduction of the cavity decay rate (γ_{cav}) comes due to the large dispersion (which can easily exceed the empty cavity dispersion in the case of optically thick medium) near to the point of almost-vanishing absorption [12–14]. The system can quench the fluorescence for all frequencies under the condition of maximum quantum interference if the detuning satisfies certain condition. Due to the quantum interference (i.e., SGC), we observe a rapid change in the refractive index near the vanishing absorption. Here the medium provides a large dispersion capable of reducing the cavity linewidth. Because of this, we can achieve the strong coupling conditions not by decreasing the effective mode volume, but by reducing the atomic decay rate (γ_a) via quantum interference, and cavity decay rate (γ_{cav}) through

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enhanced dispersion. Both of these properties have been studied recently under the induced atomic coherence and quantum interference in three-level atomic systems [10–14]. With this proposed scheme, one can investigate interesting cavity-QED effects in the optical domain with sizeable optical cavities containing atomic cells, that can be used to manipulate photon and atomic states for quantum information processing.

Recently, a hybrid absorptive-dispersive, atomic optical bistability in an open Λ-type, three-level system was studied using a microwave field to drive the hyperfine transition between two lower states, and including the incoherent pumping and spontaneously generated coherence [15]. In another work, the resonance fluorescence spectrum of a three-level, ladder system driven by two laser fields was investigated and its resemblance with a V-type system with parallel dipole moments was compared. The ladder system was experimentally studied using a ^{85}Rb atom beam, which showed the narrowing of the central peak and reminding the spontaneously generated coherence phenomenon in a V-type system responsible for such narrowing [16]. Likewise, a two-mode-entangled light generation from a laser-driven, three-level V-type atom kept inside a cavity was reported, where the spontaneously generated quantum interference between two atomic decay channels played a crucial role [17]. In reality, there is continued interest to generate SGC in cavity QED. For example, SGC was experimentally observed via its effect on the absorption spectrum in a rubidium atomic beam without imposing the rigorous requirement of close-lying levels. The experiments were carried out both in a four-level, N-type and four-level, inverted-Y-type rubidium atomic systems [18]. In a recent work, generation of SGC in a Rb atomic system was proposed using photon counting statistics in a four-level, Y-type model driven by three coherent fields; ultra narrow probe absorption peaks in the presence of SGC were also predicted [19]. The rest of the paper is organized as follows. In Section 2, we discuss the model, equations proposed, and results. Some concluding remarks are given in Section 3.

2. Model, equations, and results

In this work, we consider a model atom in a V-type configuration of its levels, consisting of two upper states $|2\rangle$ and $|3\rangle$, coupled to a common lower level $|1\rangle$ by a single-mode laser field with amplitude E_L and frequency ω_L (see Fig. 1). The Hamiltonian of the system in the rotating frame of the field of frequency ω_L is given by

$$H = (\Delta - \omega_{23})|2\rangle\langle 2| + \Delta|3\rangle\langle 3| + [(\Omega_1|2\rangle\langle 1| + \Omega_2|3\rangle\langle 1|) + H.c.], \tag{1}$$

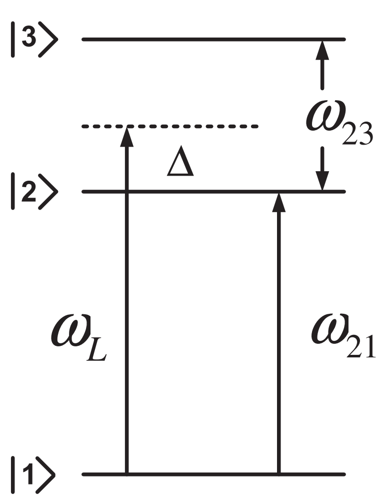

Fig. 1. Diagram of a three-level system in V-configuration driven by a laser of frequency ω_L.

where $\Delta = \omega_{21} - \omega_L$ is the detuning of the laser field frequency from level $|2\rangle$, $\Omega_k = 2(d_{k+1,1})E_L/\hbar$ (k=1,2) is the Rabi frequency, $d_{k+1,1}$ is the dipole matrix element of the atomic transition from $|1\rangle$ to $|k+1\rangle$ (k=1,2), and ω_{23} is the level splitting of the upper levels. $|m\rangle\langle n|$ is the dipole transition operator when $m \neq n$ (or the population operator when m=n). In the frame rotating with the applied field, the equations of motion of the reduced density matrix elements are

$$\begin{aligned}
\dot{\rho}_{11} &= 2\gamma_1\rho_{22} + 2\gamma_2\rho_{33} + 2\gamma_{12}(\rho_{23} + \rho_{32}) + i\frac{\Omega_1}{2}(\rho_{12} - \rho_{21}) + i\frac{\Omega_2}{2}(\rho_{13} - \rho_{31}),\\
\dot{\rho}_{22} &= -2\gamma_1\rho_{22} - \gamma_{12}(\rho_{23} + \rho_{32}) - i\frac{\Omega_1}{2}(\rho_{12} - \rho_{21}),\\
\dot{\rho}_{33} &= -2\gamma_2\rho_{33} - \gamma_{12}(\rho_{23} + \rho_{32}) - i\frac{\Omega_2}{2}(\rho_{13} - \rho_{31}),\\
\dot{\rho}_{21} &= -(i\Delta + \gamma_1)\rho_{21} + i\frac{\Omega_1}{2}(\rho_{22} - \rho_{11}) + i\frac{\Omega_2}{2}\rho_{23} - \gamma_{12}\rho_{31},\\
\dot{\rho}_{32} &= -(-i\omega_{23} + \gamma_1 + \gamma_2)\rho_{32} + i\frac{\Omega_1}{2}\rho_{31} - i\frac{\Omega_2}{2}\rho_{12} - \gamma_{12}(\rho_{22} + \rho_{33}),\\
\dot{\rho}_{31} &= -(i(\Delta - \omega_{23}) + \gamma_2)\rho_{31} + i\frac{\Omega_2}{2}(\rho_{33} - \rho_{11}) + i\frac{\Omega_1}{2}\rho_{32} - \gamma_{12}\rho_{21},
\end{aligned} \tag{2}$$

in which γ_k is the spontaneous decay constant of the excited upper levels $k+1$ (k=1,2) to the ground level $|1\rangle$. The term γ_{12} accounts for the spontaneous emission induced quantum interference effect due to the cross coupling between emission processes in the radiative channels $|2\rangle \to |1\rangle$ and $|3\rangle \to |1\rangle$. The quantum interference terms in (2) represent the physical situation in which a photon is emitted virtually in channel $|2\rangle \to |1\rangle$ and virtually absorbed in channel $|1\rangle \to |3\rangle$, or vice versa. Eq. (2) can be written in the Lindblad form. The details of such equation are mentioned in Ref. [20].

Quantum interference plays a very significant role in spectral line narrowing, fluorescence quenching, population trapping, etc. Although in a recent experiment the ability of controlling γ_{12} has been experimentally demonstrated in sodium dimers by considering the superposition of singlet and triplet states due to spin–orbit coupling [21], a conflicting result was obtained in another experiment of similar kind [22]. However, SGC was observed in an absorption experiment using rubidium atomic beam [18]. The quantum interference effect is sensitive to the atomic dipole orientation. If dipoles $\vec{d}_{21}$ and $\vec{d}_{31}$ are parallel to each other, then $\gamma_{12} = \sqrt{\gamma_1\gamma_2}$, and the interference is maximal. On the other hand, if $\vec{d}_{21}$ and $\vec{d}_{31}$ are perpendicular to each other, then $\gamma_{12} = 0$, and there is no quantum interference. We can see this more clearly by exploring the origin of such coherence. The photon emitted during spontaneous emission on one of the two atomic transitions in the system drives the other transition. The strength parameter of the coherence, represented by the coefficient γ_{12}, is directly proportional to the mutual polarization of the transition dipole moments of the two transitions characterized by $p = \cos\theta$, where θ is the angle between the two dipole moments. One can write $\gamma_{12} = \sqrt{\gamma_1\gamma_2}\cos\theta$. If the two transition dipole moments are perpendicular to each other, then p=0 and $\gamma_{12} = 0$, leading to no SGC. Similarly, if the dipole moments are parallel to each other, then p=1 and $\gamma_{12} = \sqrt{\gamma_1\gamma_2}$, leading to maximum SGC [20]. In addition to this, one can also have partial quantum interference.

The absorption (dispersion) spectrum is proportional to the real (imaginary) part of the term $\rho_{21} + \rho_{31}$. Using (2), it is straightforward to evaluate analytically this term in the steady state assuming that the dipole moments are equal and parallel. Assuming that Ω_1 and Ω_2 are real and equal ($\Omega_1 = \Omega_2 = \Omega$), and setting the two radiative damping constants to be equal, $\gamma_1 = \gamma_2 = \gamma$, the steady-state absorption and dispersion are found to be

$$A(\Delta) = \frac{2\gamma\Omega(\omega_{23} - 2\Delta)^2}{4\Delta^2(\omega_{23} - \Delta)^2 + 2\Omega^2(\omega_{23}^2 - 2\omega_{23}\Delta + 2\Delta^2) + 4\gamma^2(\omega_{23} - 2\Delta)^2 + \Omega^4}, \tag{3}$$

$$\eta(\Delta) = -\frac{2\Delta\Omega(\omega_{23} - \Delta)(\omega_{23} - 2\Delta)}{4\Delta^2(\omega_{23} - \Delta)^2 + 2\Omega^2(\omega_{23}^2 - 2\omega_{23}\Delta + 2\Delta^2) + 4\gamma^2(\omega_{23} - 2\Delta)^2 + \Omega^4}. \tag{4}$$

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