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.

Keywords: cavity quantum electrodynamics, quantum interference, three-level atom, strong atom-field coupling

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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 $\gamma_a$, and the cavity decay rate $\gamma_{cav}$. The parameter $g$ characterizes the oscillatory exchange of excitation between the atom and the cavity field mode while its magnitude relative to the parameters $\gamma_a$ and $\gamma_{cav}$ decides if the coupling between atom and resonator is weak or strong. Both the suppression and enhancement of radiative decay rate $\gamma_a$ 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 10⁶K 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 $\gamma_a$ and $\gamma_{cav}$. One can express the coupling parameter as $g = (\mu^2 \omega_0 / 2 \hbar c_0 V)^{1/2}$, where $\mu$ 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 $m_0 = \gamma_a^2 / 2 g^2$ 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 $\gamma_a$ and $\gamma_{cav}$ (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 ($\gamma_{cav}$) 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 $3 \times 10^6$ 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 ($\gamma_a$) [10, 11]. The reduction of the cavity decay rate ($\gamma_{cav}$) 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 ($\gamma_a$) via quantum interference, and cavity decay rate ($\gamma_{cav}$) through 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] and [3], coupled to a common lower level [1] by a single-mode laser field with amplitude $E_L$ and frequency $\omega_L$ (see Fig. 1). The Hamiltonian of the system in the rotating frame of the field of frequency $\omega_L$ is given by

$$H = (\Delta - \omega_23)|2\rangle\langle2| + \Delta|3\rangle\langle3| + [i(\Omega_1|2\rangle\langle1| + \Omega_2|3\rangle\langle1|) + H.c.]$$

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 $\omega_{23}$ 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

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

$$\dot{\rho}_{22} = -2\gamma_1 \rho_{22} - \gamma_{12}(\rho_{23} + \rho_{32}) - i\frac{\Omega_1}{2}(\rho_{12} - \rho_{21}),$$

$$\dot{\rho}_{33} = -2\gamma_2 \rho_{33} - \gamma_{12}(\rho_{23} + \rho_{32}) - i\frac{\Omega_2}{2}(\rho_{13} - \rho_{31}),$$

$$\dot{\rho}_{21} = -(i\Delta + \gamma_1)\rho_{21} + i\frac{\Omega_1}{2}(\rho_{22} - \rho_{11}) + i\frac{\Omega_2}{2}\rho_{23} - \gamma_{12}\rho_{31},$$

$$\dot{\rho}_{32} = -(i\omega_{23} + \gamma_1 + \gamma_2)\rho_{32} + i\frac{\Omega_1}{2}\rho_{31} - i\frac{\Omega_2}{2}\rho_{12} - \gamma_{12}(\rho_{22} + \rho_{33}),$$

$$\dot{\rho}_{31} = -(i(\Delta - \omega_{23}) + \gamma_2)\rho_{31} + i\frac{\Omega_2}{2}(\rho_{33} - \rho_{11}) + i\frac{\Omega_1}{2}\rho_{32} - \gamma_{12}\rho_{21},$$

in which $\gamma_k$ is the spontaneous decay constant of the excited upper levels $k+1$ ($k = 1, 2$) to the ground level $|1\rangle$. The term $\gamma_{12}$ accounts for the spontaneous emission induced quantum interference effect due to the cross coupling between emission processes in the radiative channels $|2\rangle \rightarrow |1\rangle$ and $|3\rangle \rightarrow |1\rangle$. The quantum interference terms in (2) represent the physical situation in which a photon is emitted virtually in channel $|2\rangle \rightarrow |1\rangle$ and virtually absorbed in channel $|1\rangle \rightarrow |3\rangle$, or vice versa. Equation (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 $\gamma_{12}$ 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 $\gamma_{12} = \sqrt{\gamma_{12}^2}$, 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 $\langle 2 \rangle$ the steady state assuming that the dipole moments are equal and parallel. Assuming that $\Omega_1$ and $\Omega_2$ 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

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

(3)

and

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

(4)

It is clear from (3) that when the laser is tuned midway between the two levels $|2\rangle$ and $|3\rangle$ (i.e., $\Delta = \omega_{23}/2$) the steady-state absorption becomes identically zero due to the destructive interference between the amplitudes of the oscillating dipoles of the two transitions. On the other hand, if the dipoles are orthogonal to each other ($\vec{d}_{21} \cdot \vec{d}_{31} = 0$) we do not observe cancellation of the absorption at $\Delta = \omega_{23}/2$. Similarly, equation (4) shows that the zeros of the dispersion spectrum are located at $\Delta = 0$, $\omega_{23}/2$, and $\omega_{23}$, respectively. Figure 2 shows the absorption and dispersion spectra as a function of the laser detuning with the conditions $|d_{21}| = |d_{31}|$, $\gamma_1 = \gamma_2 = \gamma = 0.5$, $\Omega_1 = \Omega_2 = 0.5$, and $\omega_{23} = 1$.

The above model is easier to visualize in the dressed-state representation. For simplicity, we keep the condition $\Delta = \omega_{23}/2$, and the magnitudes of both dipole moments identical (i.e., $\Omega_1 = \Omega_2 = \Omega$ and $\gamma_1 = \gamma_2 = \gamma$). The eigenvalues of the interaction Hamiltonian are $Z_a = -\Omega_{\text{eff}}/2$, $Z_b = 0$, and $Z_c = -\Omega_{\text{eff}}/2$ (where $\Omega_{\text{eff}} = \sqrt{(\omega_{23})^2 + 8(\Omega)^2}$). We further assume that $\Omega_{\text{eff}}$ is greater than all relaxation rates. The steady state population of the dressed states are given by [23]

$$\rho_{aa} = \frac{(\Gamma_a - \Gamma_c)}{4\Gamma_a} = \rho_{cc},$$
\begin{equation}
\rho_{bb} = \frac{\Gamma_a}{\Gamma_c}, \tag{5}
\end{equation}

with \( \Gamma_a \) and \( \Gamma_c \) representing the decay constants related to the dressed states, and expressed as

\[
\Gamma_a = (\gamma + \gamma_{12})y^2 + (\gamma - \gamma_{12})(3y^4 - 4y^2 + 2),
\]

\[
\Gamma_c = \frac{1}{2} [(\gamma + \gamma_{12})y^2 + (\gamma - \gamma_{12})y^4],
\]

\[
y = \frac{\omega_{23}}{\Omega_{\text{eff}}}. \tag{6}
\]

If maximum quantum interference is present in the system, then \( \gamma_{12} = \gamma, \rho_{aa} = \rho_{cc} = 0, \rho_{bb} = 1 \), the population is entirely trapped in the dressed state \(|b\rangle\), and there is zero absorption at \( \Delta = \omega_{23}/2 \). Thus the destructive quantum interference is responsible for this zero absorption. On the other hand, if \( \gamma_{12} = 0 \) then the absorption is almost near maximum depending upon the value of \( \Omega \) with respect to \( \omega_{23} \). However, if \( \gamma_{12} \) is slightly lower than its maximum value \( \gamma \), then destructive quantum interference will not be complete but still a considerable amount of population will be trapped in the dressed state \(|b\rangle\) and some population will be available in the dressed states \(|a\rangle\) and \(|b\rangle\).

Consequently, some decay of population from the dressed state \(|b\rangle\) takes place with decay constant equal to \( \gamma y^2 \). If \( y \ll 1 \), then the splitting \( \omega_{23} \) of the upper two levels is much less than the effective Rabi frequency \( \Omega_{\text{eff}} \), and the decay constant of the dressed state \(|b\rangle\) is much smaller than \( \gamma \), i.e., \( \Gamma_b \ll \gamma \). Such small decay constant is responsible of producing narrow Lorentzian peaks in the fluorescence spectrum [23]. At this stage, we would like to emphasize that for observing population trapping in the dressed state we need not have two Rabi frequencies to be equal. As long as the dipole moments of two transitions are parallel and \( \Delta = \omega_{23}/(1 + a^2) \), with \( a \) a real number, the population trapping would take place irrespectively of the actual value of \( a, \omega_{23} \) and \( \Omega_{\text{eff}} \).

In the discussion above, we keep the atomic system in a vapor cell of unity length in an optical cavity of length \( \ell \). We can separate the susceptibility \( \chi \) of the medium in its imaginary and real parts, \( A \) and \( \eta \), as mentioned above in (3) and (4), respectively. The absorption coefficient of the medium is related with the imaginary part:

\[
\alpha = \left( \frac{n_0 \omega L}{c} \right) A,
\]

in which \( n_0 \) is the refractive index of background. The resonant frequency of the cavity is pulled due to the dispersion caused by the intracavity medium, and in accordance with the relation

\[
\omega_r = \frac{1}{1 + \zeta} \omega_C + \frac{\zeta}{1 + \zeta} \bar{\omega}, \tag{7}
\]

where \( \omega_C \) is the resonant frequency of the empty cavity and \( \bar{\omega} \) is the average of the two atomic transition frequencies [12–14]. The parameter \( \zeta = \omega_r (s/2\ell) (\partial \chi'/\partial \omega_L) \) is the change in dispersion with respect to the laser frequency. It is easy to show that due to the presence of a dispersive medium in the cavity, there is a change in the linewidth of the cavity resonance over its empty cavity linewidth. The ratio of these two linewidths is given by

\[
\frac{\gamma_m}{\gamma_e} = \frac{1 - R\kappa}{\sqrt{\kappa(1 - R)}} \frac{1}{1 + \zeta}, \tag{8}
\]

in which \( \gamma_e \) is the linewidth of the empty cavity, \( \gamma_m \) is the linewidth of the cavity with the medium, \( R \) is the reflectivity of both mirrors, and \( \kappa = \exp(-\alpha s) \) is related to the
absorption in a single pass. Figure 7 of Ref [14] clearly depicts the experimental demonstration of line narrowing in cavity transmission profile due to the dispersive medium present in the cavity (Fig. 2 of this manuscript shows the dispersion). Note that, if we consider the two-level atomic medium in the cavity and say the $\omega_r$ is near to the atomic transition frequency, the dispersion becomes larger causing a narrowing of the linewidth, but at the same time the absorption also becomes larger cancelling the narrowing effect. In the case of the atomic model under consideration, if coherence (SGC) is present in the system (parametric condition of Fig. 2) then the cavity transmission spectrum shows line narrowing as depicted in Fig. 3 for the central peak (see Ref [23]).

Having established the reduction of cavity’s and dressed state’s decay rates, we are certainly in a situation that allows to carry out cavity QED experiments in the optical regime without the need of decreasing the cavity mode volume or requiring high finesse of the optical cavity. One such example of strong coupling cavity QED experiments in optical regime is the observation of vacuum Rabi-splitting (VRS) spectrum [6, 24–26]. In Fig. 4, we showed one peak of the VRS spectrum (the other peak is symmetrically located on the other side) for the V-system (including SGC) under consideration within the formalism of linear absorption-dispersion theory and interference of multiple beams [24, 25]. We obtained the location of the VRS peaks using the dressed state picture. The eigenvalues and the eigenstates [10, 11, 27] for the system are

$$
\begin{align*}
0, \frac{2g\sqrt{n+1}}{\Omega_N},\frac{2g\sqrt{n+1}}{\Omega_N} \pm \frac{\omega_{23}}{2} 
\end{align*}
$$

where $\Omega_N = \frac{1}{2}[\omega_{23} + 8g^2(n + 1)]^{1/2}$. The VRS spectrum is the transition from ground state to the first manifold of the dressed state [26]. Clearly, the peaks are located at $\omega_{23}/2$, $\omega_{23}/2 \pm \sqrt{2g}$.

To achieve SGC in this system, we need to have parallel dipole moments for the two transitions, which is difficult to achieve practically. However, in a recent proposal (see Ref [28]), it is claimed that there is no need to have parallel dipole moments to achieve strong quantum interference in such system. One can work with the perpendicular dipole moments but it requires cw field to drive the transition between the upper atomic states. This system exhibits the same features shown by that with parallel dipole moments.

We expect that this work could be applicable for cavity cooling experiments of single atoms [29].

3. Conclusions

In this work, we proposed an alternative scheme to carry out a strong coupling, cavity quantum electrodynamics experiments in the optical regime using spontaneously generated coherence and enhanced dispersion. To do this, we considered a V-type, three-level atomic system interacting with a single mode field inside an optical cavity. Then, we showed by a sample calculation that the spontaneously generated coherence and
enhanced dispersion in this system considerably reduced the radiative and cavity decay rates when the laser is tuned midway between the two excited levels $|2\rangle$ and $|3\rangle$ (i.e., $\Delta = \omega_{23}/2$), maximizing the quantum interference in the system. However, there was no restriction in the selection of $\Delta$.

To elaborate our proposal quantitatively, we compared our results with the following fundamental rates of strong coupling regime obtained by Thompson et al. [25]:

$$(g, \gamma_\perp, \gamma_{\text{cav}}) = [2\pi (3.2, 2.5, 0.9)] \text{MHz} \text{ (here, } \gamma_\perp = \gamma_a/2).$$

The $g$ can be calculated from its definition $g = (\mu^2 \omega_0 / 2 \hbar \epsilon_0 V)^{1/2}$. Clearly, $g$ depends on the cavity-mode volume $V = \pi w_0^2 \ell / 4$, where $w_0$ is the mode waist and $\ell$ is the length of the cavity. In our proposal, the atomic decay constant decreased by a factor between 10 and 100 due to SGC [18, 19, 23]; the cavity decay constant also decreased by a factor of 14 [12–14] due to enhanced dispersion and requiring a lower finesse cavity; and the critical photon number and atom number remain more or less the same. Therefore, we can have $g$ lowered by a factor of 10. This means one can work with a higher mode volume this time. Consequently, we may have a cavity length and a mode waist 20 and 2.2 times larger than those used in that experiment, respectively. Perhaps, this will allow the use of larger cavities with lower finesse cavity. This observation offers a new perspective in cavity quantum electrodynamics experiments as it shows that the use of expensive miniaturized cavity with high finesse may not longer be required.

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Figure 1: Diagram of a three-level system in V-configuration driven by a laser of frequency $\omega_L$. 
Figure 2: Absorption $A$ and dispersion $\eta$ versus detuning $\Delta$ as given by equations (3, 4) for $\gamma = 0.5$, $\Omega = 0.5$, and $\omega_{23} = 1$. The left and right peaks for the absorption curve occur at $\Delta = -0.1, 1.1$, respectively. The trough is located at $\Delta = 0.5$. 
Figure 3: Transmitted light intensity from the optical cavity versus atomic detuning $\Delta$ for different values of the induced quantum interference $\gamma_{12}$, with $\gamma' = \sqrt{\gamma_1 \gamma_2}$. The spontaneous decay constants are $\gamma_1 = \gamma_2 = 0.05$, the Rabi frequencies $\Omega_1 = \Omega_2 = 0.1$, and the level splitting $\omega_{23} = 0.3$. Maximum transmission occurs at $\Delta = 0.15$. 

\[ \gamma_{12} = 0.0 \gamma' \quad \gamma_{12} = 0.7 \gamma' \quad \gamma_{12} = 0.9 \gamma' \]
Figure 4: Peak of the vacuum Rabi-splitting spectrum (VRS) for the same system of Fig. 3, and including SGC.

\[ \gamma_{12} = 0.0 \gamma' \]  
\[ \gamma_{12} = 0.7 \gamma' \]  
\[ \gamma_{12} = 0.9 \gamma' \]