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Dynamic properties of atomic collective decay in cavity quantum electrodynamics*

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We theoretically study the collective decay of two atoms trapped in a single mode cavity and we describe the evolution of the population of Dicke states. We show that the collective decay property is strongly dependent on the phase of atomic radiation and the speeding up of collective decay can only be observed in a bad cavity regime. For in- or out-phase case, this occurs due to the quantum interference enhancement, no matter which atom is excited initially. For $\pi/2$ phase, the speeding up of collective decay takes place if the first atom is excited at the beginning. However, it disappears due to the quantum interference cancellation if the second atom is excited. Compared with the in-phase and out-phase cases, we also show that the speeding up of collective decay can be significantly enhanced in strong coupling regime for $\pi/2$ phase, although one atom is decoupled to the cavity in this condition. The study presented here is helpful to understand the physical mechanism of collective decay in cavity quantum electrodynamics and it provides a useful method to control the collective decay phenomenon via quantum interference effect.

Keywords: quantum interference, collective decay, cavity quantum electrodynamics

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1. Introduction

Quantum interference effects are basic features of quantum mechanics, they are also the foundation of quantum optics. There are various interesting optical phenomena that are essentially based on quantum interference effects, for example: electromagnetically induced transparency,[1] lasing without inversion (LWI),[2,3] and refractive index enhancement without absorption.[4] In addition, quantum interference can lead to the modification of atomic spontaneous emission, such as, spontaneous emission enhancement in photonic crystals[5,6] and reduction even cancellation in three-level atoms.[7–9]

It is well-known that the spontaneous emission rate emitted by quantum emitters can be modified by inhomogeneity of the cavity environment in the Purcell effect.[10] Purcell also demonstrated that the spontaneous emission rate is not an intrinsic property of the emitter. Since then, great attention has been drawn on resonant systems to study the enhancement of the spontaneous emission decay rate, such as plasmonic waveguides,[11] photonic crystals,[6,12,13] nanocavities,[14,15] and nanoshells.[16] However, it is hard to enhance the total (collective) emission in an ensemble of quantum emitters system due to the severe condition of the emitters' accurate location as well as the neighboring large and homogeneous electric field distributions in resonating systems.

Collective emission or decay occurs in an ensemble of quantum emitters system where the emitters are coupled to a lossy cavity[17,18] or close to each other.[19,20] Collective decay is of fundamental interest in quantum optics and has attracted tremendous attention[21] since the seminal work by Dicke,[22] especially relating to the phenomenon to super-radiance.[19,23–26] The phenomenon can be attributed to the constructive quantum interference between emitted waves and has been widely investigated in various photonic environments.[27–33] Through coherent control of collective decay, the super-radiant states can be converted into subradiant ones and *vice versa* in an extended atomic ensemble.[34] Chen *et al.* proposed a scheme to realize entanglement swapping via collective decay, which is a procedure to create entanglement between two qubits.[35] Agarwal *et al.* showed determinstic generation of Werner states of the collective decay dynamics of a pair of neutral atoms coupled to a leaky cavity and strong coherent drive.[36] Wang *et al.* also presented a simple scheme to effectively generate maximal pure-state entanglement between non-interacting atoms through purely collective decay.[37] Despite all of these research achievements, the nature or physical mechanism of collective decay is, even today, not well understood.

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In this paper, we have carefully studied the dynamics of atomic collective decay in cavity quantum electrodynamics. We assume that two atoms are trapped in a single mode cavity with different positions and that one of them is initially excited by a single photon. It is found that the decay properties of the Dicke states are strongly dependent on the phase between two atoms. We show that the speeding up of collective decay can only be observed in the bad cavity regime due to the quantum interference effect. In the case of in-phase or out-phase radiation, the decay rate of the Dicke state is much faster than that of the single atom, which is recognized as a witness of the single photon super-radiance.[38] Here, it should be emphasized that the obtained single photon super-radiance is referred to the collective decay enhancement of two atoms trapped in a cavity via single photon excitation comparing with the spontaneous decay of one atom in vacuum. We also show that the properties of the collective radiation change significantly if the atoms feel different coupling strengths to the cavity. For example, in the case of $\pi/2$ phase, the speeding up of the collective decay can be observed when the first atom is excited initially, while it disappears if the second atom is excited at the beginning. Particularly, in the case of $\pi/2$ phase, the speeding up of the collective decay can be significantly enhanced by increasing the coupling strength. The results presented in this work are helpful for understanding the nature of the collective decay phenomenon in the cavity and can be implemented in other systems.

2. Bad cavity regime

To begin with, we consider that two two-level atoms with the same resonant transition frequency ω_A are weakly coupled to a single mode cavity with frequency ω_C [see Fig. 1(a)]. State $|g\rangle$ ($|e\rangle$) corresponds to the ground (excited) state of each atom, and γ denotes the spontaneous decay rate from state $|e\rangle$ to state $|g\rangle$. Since the two atoms are located at different positions, the coupling strengths between atoms and cavity are different and denoted by g_1 and g_2 respectively.

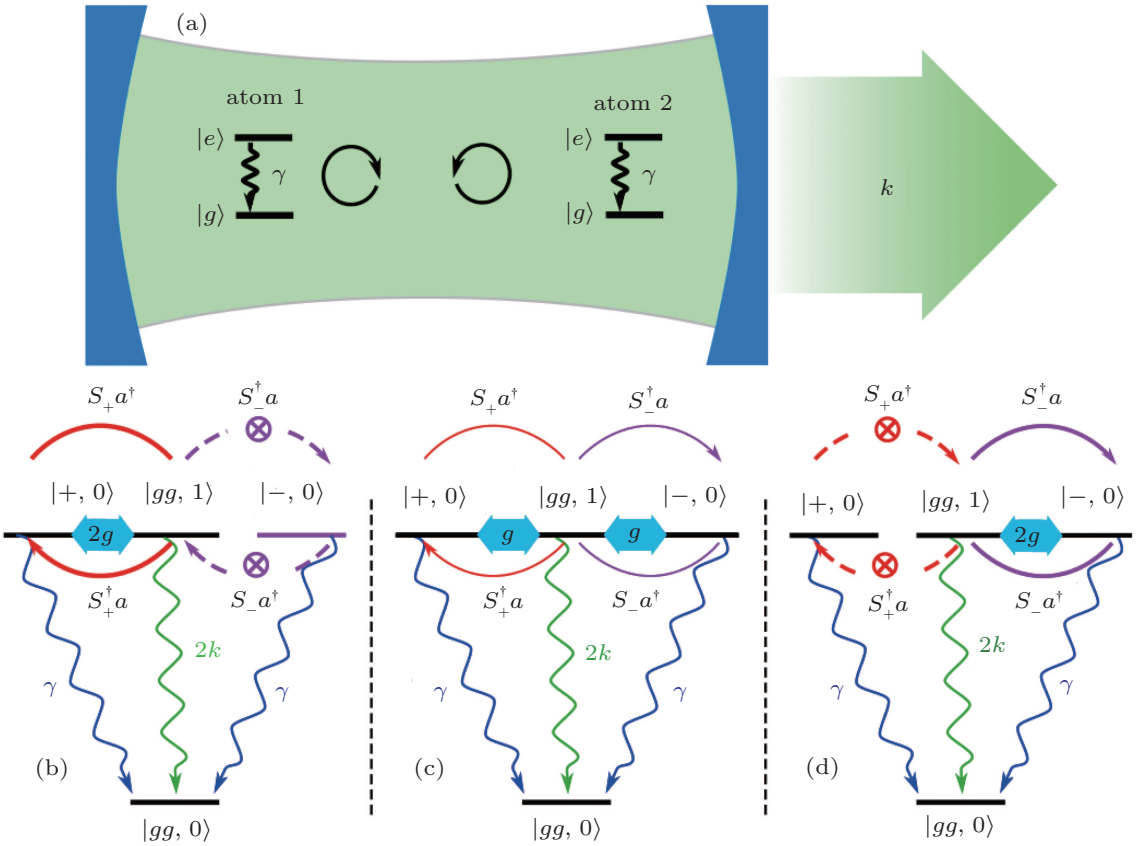


Fig. 1. (color online) Physical model sketch and Dicke state diagram. (a) Two atoms are trapped in a single mode cavity with different positions. The ground (excited) state of each atom is labeled as $|g\rangle$ ($|e\rangle$). γ and κ represent the decays of atoms and cavity, respectively. The coupling strengths between atom and cavity are denoted by g_1 and g_2 respectively. (b)–(d) The coupling and decay between the lowest four Dicke states for phases between two atoms $\phi_z = 0$, $\pi/2$, and π, respectively. Here, we define the collective states $|\pm,0\rangle = (|eg,0\rangle \pm |ge,0\rangle)/\sqrt{2}$.

The dynamical evolution of this atom–cavity coupled system can be well described by the Jaynes–Cummings Hamiltonian in the frame rotating with the cavity frequency,[39,40] *i.e.*,

$$H_{\rm I} = \hbar\left[\Delta_A(S_+^1 S_-^1 + S_+^2 S_-^2) + g_1(a^\dagger S_-^1 + aS_+^1) + g_2(a^\dagger S_-^2 + aS_+^2)\right], \quad (1)$$

where $\Delta_A = \omega_A - \omega_C$ is the detuning of the atomic resonance frequency from the cavity frequency. S_+^j (S_-^j) is the raising (lowering) operator for the j-th two-level atom, and $a^\dagger$ (a) is the cavity photon creation (annihilation) operator. For simplicity, we can assume that the first atom is localized at the

antinode of the standing wave in the cavity, so that the coupling strength between the first atom and the cavity is $g_1 = g_0$. Then, the coupling strength between the second atom and the cavity is $g_2 = g_0\cos(\phi_z)$ with $\phi_z = 2\pi\Delta z/\lambda_C$ being the phase shift between the radiation of the two atoms. Here, Δz is the distance between two atoms and $\lambda_C = c_0/\omega_C$ is the wavelength of the cavity mode where c_0 is the light speed in vacuum.

In the normalized unit with $\hbar = 1$, the evolution of the density matrix ρ of this system, including all the dephasing terms, is given by

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\mathrm{i}\left[H_\mathrm{I},\rho\right] + \mathscr{L}_\mathrm{atom}\rho + \mathscr{L}_\mathrm{cav}\rho, \tag{2}$$

where

$$\mathscr{L}_\mathrm{atom}\rho = -\gamma\sum_{j=1}^{2}(S_+^jS_-^j\rho - 2S_-^j\rho S_+^j + \rho S_+^jS_-^j)$$

and

$$\mathscr{L}_\mathrm{cav}\rho = -\kappa(a^\dagger a\rho - 2a\rho a^\dagger + \rho a^\dagger a)$$

originate from the spontaneous decay of each two-level atom at rate 2γ and the decay of the cavity field at rate 2κ. It is obvious that the collective decay rate is phase-dependent and results in the super-radiance and subradiance effects.

In general, equation (2) can only be solved numerically since high-order photon states must be considered in the strong coupling regime. However, for a bad cavity and weak coupling strengths, only few photons in the cavity can interact with the atoms so that the master equation can be simplified by neglecting the cavity component, yielding

$$\begin{aligned}\frac{\mathrm{d}\rho}{\mathrm{d}t} = &-\gamma\sum_{j=1}^{2}(S_+^jS_-^j\rho - 2S_-^j\rho S_+^j + \rho S_+^jS_-^j)\\ &-\frac{g_0^2}{\kappa}(R_+R_-\rho - 2R_-\rho R_+ + \rho R_+R_-),\end{aligned} \tag{3}$$

where $R_\pm = S_\pm^1 + g_2S_\pm^2/g_1 = S_\pm^1 + \cos(\phi_z)S_\pm^2$ are the effective operators for Dicke states.

Considering the lowest three states of this simplified system for single photon excitation, *i.e.*, $|1\rangle = |gg\rangle$, $|2\rangle = |eg\rangle$, and $|3\rangle = |ge\rangle$, we can obtain a set of equations from Eq. (3), which reads

$$\dot\rho_{22} = -2\left(\gamma_+\frac{g_0^2}{\kappa}\right)\rho_{22} - \frac{2g_0^2}{\kappa}\cos\phi_z\mathrm{Re}(\rho_{23}), \tag{4a}$$

$$\dot\rho_{33} = -2\left(\gamma + \frac{g_0^2}{\kappa}\cos^2\phi_z\right)\rho_{33} - \frac{2g_0^2}{\kappa}\cos\phi_z\mathrm{Re}(\rho_{23}), \tag{4b}$$

$$\begin{aligned}\dot\rho_{23} = &-2\left[\gamma + \frac{g_0^2}{\kappa}(1+\cos^2\phi_z)\right]\rho_{23}\\ &-\frac{g_0^2}{\kappa}\cos\phi_z(\rho_{33}-\rho_{22}),\end{aligned} \tag{4c}$$

where $\rho_{ij} = \rho_{ji}^* = \langle i|\rho|j\rangle$, and $\sum_{j=1}^3\rho_{jj} = 1$ for conversation. Here, we must point out that the population of state $|ee\rangle$ is zero since there is only one photon in the cavity.

If one assumes $\gamma\tau \gg 1$ or $g_0^2\tau/\kappa \gg 1$ with τ being the time scale of interaction, equation (4c) can be solved under the steady state approximation, *i.e.*,

$$\rho_{23} \approx -\frac{g_0^2\cos(\phi_z)(\rho_{33}-\rho_{22})}{2[\gamma\kappa + g_0^2(1+\cos^2(\phi_z)]}. \tag{5}$$

Then, by inserting the above equation into Eqs. (4a)–(4b) and using the initial condition $\rho_{33}(0) = 1$ (*i.e.*, the system is initially prepared in state $|3\rangle = |ge\rangle$), we can obtain the populations in states $|eg\rangle$ and $|ge\rangle$, *i.e.*,

$$P_{eg} = \rho_{22}(t) = \frac{\Gamma}{\Lambda_+ - \Lambda_-}(\mathrm{e}^{\Lambda_+ t} - \mathrm{e}^{\Lambda_- t}), \tag{6a}$$

$$P_{ge} = \rho_{33}(t) = \frac{\Lambda_+ - K_2}{\Lambda_+ - \Lambda_-}\mathrm{e}^{\Lambda_- t} - \frac{\Lambda_- - K_2}{\Lambda_+ - \Lambda_-}\mathrm{e}^{\Lambda_+ t}, \tag{6b}$$

where $\Lambda_\pm = [K_1 + K_2 \pm \sqrt{(K_1-K_2)^2 - 4\Gamma^2}]/2$ with $K_1 = -[\Gamma + 2(\gamma + g_0^2/\kappa)]$, $K_2 = \Gamma - 2(\gamma + g_0^2\cos^2(\phi_z)/\kappa)$, and $\Gamma = g_0^4\cos^2(\phi_z)/[2\gamma\kappa^2 + g_0^2\kappa(1+\cos^2\phi_z)]$.

Equations (6a) and (6b) predict many interesting characteristics for the dynamical evolution of populations in states $|eg\rangle$ and $|ge\rangle$. For example, it is noted that if the phase between the two atoms satisfy $\phi_z = \pi/2$, the first atom will not be excited [*i.e.*, $P_{eg}(t) = 0$], and the population in state $|ge\rangle$ decays at rate 2γ [*i.e.*, $P_{ge}(t) = \exp(-2\gamma t)$]. However, in the case of $\phi_z = 0$ or π, we can obtain $\Lambda_+ = \Lambda_- = -2(\gamma\kappa + g_0^2)/\kappa$. Therefore, it is easy to find that $P_{eg}(t) \approx \Gamma t$ and $P_{ge}(t) = \exp(\Lambda_+ t)$, which implies that the population in state $|eg\rangle$ will experience a linear gain at the beginning, and an enhanced damping of the population in state $|ge\rangle$ can be observed.

The physical mechanism can be understood by rewriting the Hamiltonian by using the collective states $|gg\rangle$, $|\pm\rangle = (|eg\rangle \pm |ge\rangle)/\sqrt{2}$, and $|ee\rangle$ as basis.[41] To this end, the Hamiltonian can be expressed in terms of the collective operators $S_\pm^\dagger = (S_+^1 \pm S_+^2)/\sqrt{2}$, yielding $H_\mathrm{I} = H_+ + H_-$ with $H_\pm = \hbar g_\pm(aS_\pm^\dagger + a^\dagger S_\pm)/\sqrt{2}$ and $g_\pm = g_0(1\pm\cos\phi_z)$. Using the initial condition, we can obtain that $|\pm,0\rangle = \pm|ge,0\rangle/\sqrt{2}$ at the beginning. For the case of $\phi_z = 0$ ($\phi_z = \pi$), only $|+,0\rangle \leftrightarrow |gg,1\rangle$ ($|-,0\rangle \leftrightarrow |gg,1\rangle$) coupling is allowed but the $|-,0\rangle \leftrightarrow |gg,1\rangle$ ($|+,0\rangle \leftrightarrow |gg,1\rangle$) coupling is forbidden [see Figs. 1(b) and (d)]. Thus, the single photon super-radiance can be observed via the constructive interference between $|+,0\rangle \leftrightarrow |gg,1\rangle \rightarrow |gg,0\rangle$ ($|-,0\rangle \leftrightarrow |gg,1\rangle \rightarrow |gg,0\rangle$), and $|+,0\rangle \rightarrow |gg,0\rangle$ ($|-,0\rangle \rightarrow |gg,0\rangle$) pathways. However, for the case of $\phi_z = \pi/2$, both $|+,0\rangle \leftrightarrow |gg,1\rangle$ and $|-,0\rangle \leftrightarrow |gg,1\rangle$ couplings are allowed [see Fig. 1(c)], but the coupling strengths have opposite sign, which results in an destructive interference and the decay rate of the state $|ge\rangle$ remains that of single atom (*i.e.*, 2γ).

To verify this analysis, we numerically solve Eqs. (2) and plot the populations in states $|eg\rangle$ [panel (a)] and $|ge\rangle$ [panel (b)] as functions of the phase ϕ_z and the evolution time t in Fig. 2.

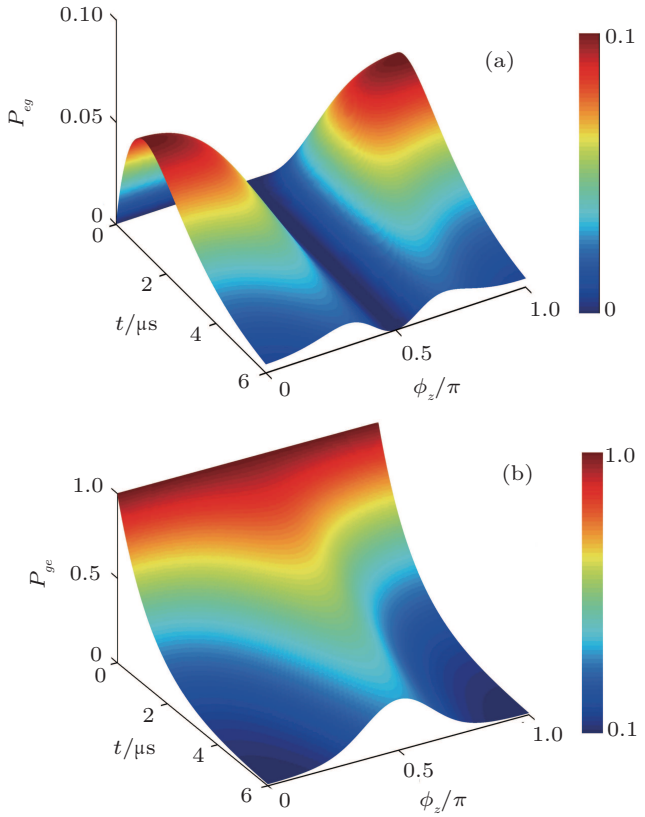


Fig. 2. (color online) The populations in states $|eg\rangle$ [panel (a)] and $|ge\rangle$ [panel (b)] with initial condition $P_{eg}(0) = 0$ and $P_{ge}(0) = 1$. The system parameters are chosen as $g_0 = 1$, $\kappa = 3$, and $\Delta_A = 0$.

The initial conditions are chosen as $P_{eg}(0) = 0$ and $P_{ge}(0) = 1$. Here, we choose the system parameters as $g_0 = 1$, $\kappa = 3$, and $\Delta_A = 0$. If one chooses $\phi_z = \pi/2$ where the population in state $|ge\rangle$ exponentially decays at the rate of 2γ [see panel (b) of Fig. 2], which is the same as the spontaneous emission rate for the single atom. The first atom is always in state $|g\rangle$, *i.e.*, $P_{eg}(0) = 0$ [see panel (a) of Fig. 2]. However, if $\phi_z \neq \pi/2$, the population in state $|ge\rangle$ drops more quickly than the rate of 2γ and reaches the maximum when $\phi_z = 0$ and π, as shown in panel (b) of 2. Simultaneously, the first atom absorbs the photon emitted from the second atom and jumps to the excited state, *i.e.*, $P_{eg}(0) \neq 0$. In the case of in-phase or out-phase radiation, the possibility in the excited state for the first atom can be maximumly achieved due to the constructive interference effect [see panel (a) of Fig. 2].

Next, we will study the collective decay effects if the two atoms are initially prepared in state $|eg\rangle$ (*i.e.*, $P_{eg}(0) = 1$ and $P_{ge}(0) = 0$). Using the same method, the solutions of Eqs. (4a)–(4c) can be obtained easily, which reads

$$P_{eg}(t) = \frac{\Lambda_+ - K_2}{\Lambda_+ - \Lambda_-} e^{\Lambda_+ t} - \frac{\Lambda_- - K_2}{\Lambda_+ - \Lambda_-} e^{\Lambda_- t}, \tag{7a}$$

$$P_{ge}(t) = \frac{\Gamma}{\Lambda_+ - \Lambda_-} (e^{\Lambda_+ t} - e^{\Lambda_- t}). \tag{7b}$$

The solutions are similar to those given in Eqs. (6a) and (6b), but hold different dynamical properties. Assuming $\phi_z = 0$ or π, we can obtain $P_{eg}(t) = \exp\left[-2(\gamma\kappa + g_0^2)t/\kappa\right]$, which implies that the population in state $|eg\rangle$ decays at the rate of $2(\gamma + g_0^2/\kappa)$. In fact, the factor g_0^2/κ represents the Purcell effect. This enhancement of the decay can also be explained by constructive quantum interference resulting from the additional pathway of $|+,0\rangle \leftrightarrow |gg,1\rangle \rightarrow |gg,0\rangle$ ($|-,0\rangle \leftrightarrow |gg,1\rangle \rightarrow |gg,0\rangle$) [see Figs. 1(b) and 1(d)]. In the case of $\phi_z = \pi/2$, the population in state $|eg\rangle$ is also $P_{eg}(t) = \exp\left[-2(\gamma\kappa + g_0^2)t/\kappa\right]$. Contrary to the case of $P_{ge} = 1$ as the initial condition, the decay rates of the state $|eg\rangle$ are always enhanced, even if only single atom is coupled to the cavity. This feature can be attributed to the constructive quantum interference between the pathways of $|+,0\rangle \leftrightarrow |gg,1\rangle$ and $|-,0\rangle \leftrightarrow |gg,1\rangle$ [see Fig. 1(c)] which have the same coupling strength when $\phi_z = \pi/2$.

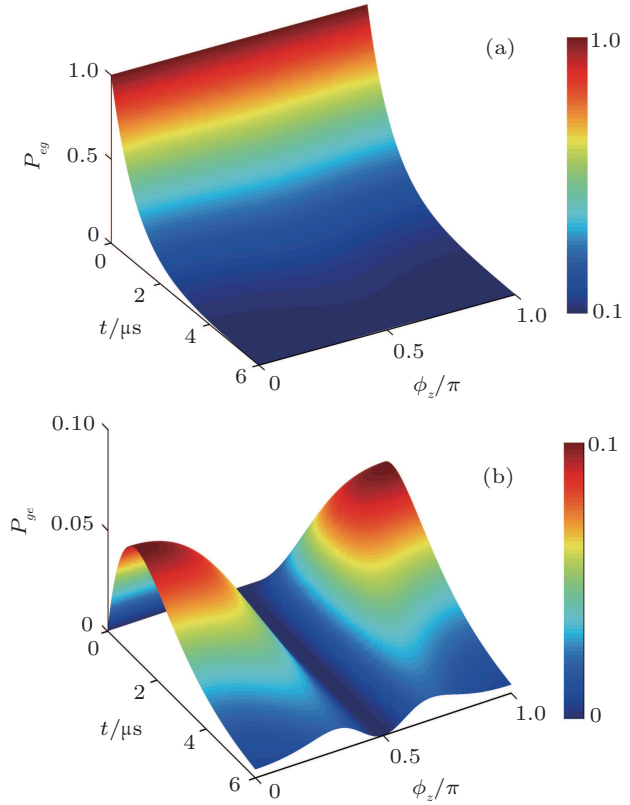


Fig. 3. (color online) The populations in states $|eg\rangle$ [panel (a)] and $|ge\rangle$ [panel (b)] with initial condition $P_{eg}(0) = 1$ and $P_{ge}(0) = 0$. The system parameters are the same as those used in Fig. 2.

By once more numerically solving Eqs. (2) with initial conditions of $P_{eg}(0) = 1$ and $P_{ge}(0) = 0$, we show the dynamical evolution of the populations in states $|eg\rangle$ and $|ge\rangle$ versus the normalized phase ϕ_z and the evolution time t in Fig. 3. The system parameters are the same as those used in Fig. 2. It is clear that the decay rate of the state $|eg\rangle$ is always enhanced (*i.e.*, bigger than 2γ, which is the spontaneous decay rate in vacuum) and almost independent of the phase between two atoms [see panel (a) of Fig. 3]. In the case of $\phi_z = \pi/2$, the second atom is always in ground state for the reason of uncoupling with the cavity. However, if $\phi_z \neq \pi/2$, the second atom exchanges energy with the first atom via coupling with the cav-

ity and the possibility of detecting the states $|ge\rangle$ reaches the maximum in case of $\phi_z = 0$ or $\phi_z = \pi$ [see panel (b) of Fig. 3].

3. Bad cavity and strong coupling regime

Now, we consider the case of $g_0 \gg \kappa, \gamma$, *i.e.*, the strong coupling regime. Since the back reaction becomes important in this case, equation (2) must be solved numerically to study the dynamical evolution of the decay in Dicke states, nevertheless, equation (3) is not effective. To make the results more explicit, only the cases of $\phi_z = 0$ and $\phi_z = \pi/2$ will be adopted under consideration in the following discussion (the case of $\phi_z = \pi$ is the same as $\phi_z = 0$).

As shown in Fig. 4, we show the dynamical evolution of populations in states $|eg\rangle$ and $|ge\rangle$ with the coupling strength $g_0 = 0.01$ (the blue curve), $g_0 = 1$ (the green curve), and $g_0 = 10$ (the red curve), respectively. Here, we first take the initial condition as $P_{eg}(0) = 0$ and $P_{ge}(0) = 1$. In the case of $\phi_z = 0$, we find that when the coupling strength between the atom and cavity is weak (*e.g.* $g_0 = 0.01$), the population in the state $|ge\rangle$ decays slowly at the approximate rate of 2γ [see blue curves in panel (b)], which is the same as the spontaneous emission rate for the single atom. The first atom cannot absorb the photon emitted from the second atom and remain in the ground state due to weak coupling strength [see the blue curve in panel (a)]. As the coupling strength increases, we show that the population in the state $|ge\rangle$ decays far more quickly than spontaneous emission for the single atom in vacuum [see the green curve in panel (b)]. Meanwhile, the possibility of being excited for the first atom by absorbing the photon emitted from the second atom gradually increases [see the green curve in panel (a)]. For strong coupling strength (here we choose $g_0 = 10$), the decay rate of the population in the state $|ge\rangle$ increases further. Resulting from the strong coupling, resonance between $|+,0\rangle \leftrightarrow |gg,1\rangle$ makes both P_{eg} and P_{ge} oscillate intensively at the frequency $2\pi/(\sqrt{2}g_0)$ [see the red curves in panels (a) and (b) in Fig. 4]. Moreover, two atoms continuously exchange energy from each other via the cavity. Therefore, the possibility of detecting the states $|eg\rangle$ exceeds 50 percent.

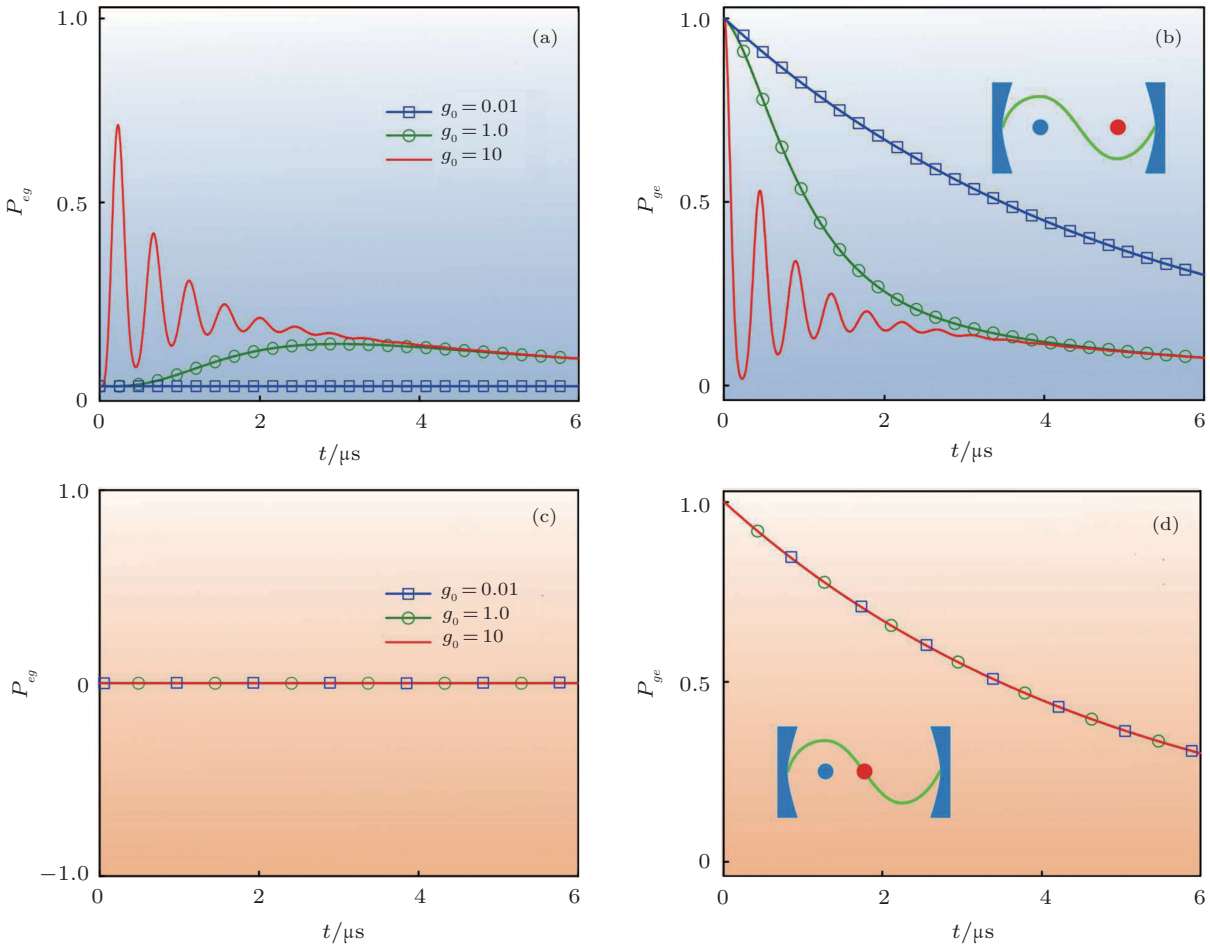


Fig. 4. (color online) The populations in states $|eg\rangle$ [panels (a) and (c)] and $|ge\rangle$ [panels (b) and (d)] with initial conditions of $P_{eg}(0) = 0$ and $P_{ge}(0) = 1$. Here, $\phi_z = 0$ for the top two panels, but $\phi_z = \pi/2$ for the button ones. The coupling strength is chosen as $g_0 = 0.01$ (blue curve), $g_0 = 1$ (green curve), and $g_0 = 10$ (red solid curve). Other system parameters are the same as those in Fig. 2.

In the case of $\phi_z = \pi/2$, we show that the decay rate of state P_{ge} is the same as that for the single atom, and $P_{eg} = 0$ no matter how strong the coupling strength is [see panels (c) and (d) in Fig. 4]. This is because the quantum destructive interference takes

place between the $|+,0\rangle \leftrightarrow |gg,1\rangle$ and $|-,0\rangle \leftrightarrow |gg,1\rangle$ couplings. We must point out that only in this case is the second atom transparent to the cavity.

In Fig. 5, we choose $P_{eg}(0) = 1$ and $P_{ge}(0) = 0$ as the initial condition. Other system parameters are the same as those used in Fig. 4. It is clear that, in the case of $\phi_z = 0$, the decay rate for P_{eg} increases with the increasing coupling strength. For strong coupling, P_{eg} demonstrates damped oscillation with the frequency of $2\pi/(\sqrt{2}g_0)$ [see panel (a)]. At the same time, we discover that the possibility of being excited for the second atom by absorbing the photon emitted from the first atom also increases with the increasing coupling strength [see the green curve in panel (b)]. For strong coupling, P_{ge} also exhibits damped oscillation with the same frequency with P_{eg} [see the red curve in panel (b)]. Now, the decay rate for the first atom increases with the increasing coupling strength, which is the well-known Purcell effect.[9] In the case of $\phi_z = \pi/2$, P_{eg} shows Rabi oscillation but with the frequency of $2\pi/(2g_0)$ [see panel (c)]. However, the population of the state $|ge\rangle$ is always zero [see panel (d)] due to destructive interference effect.

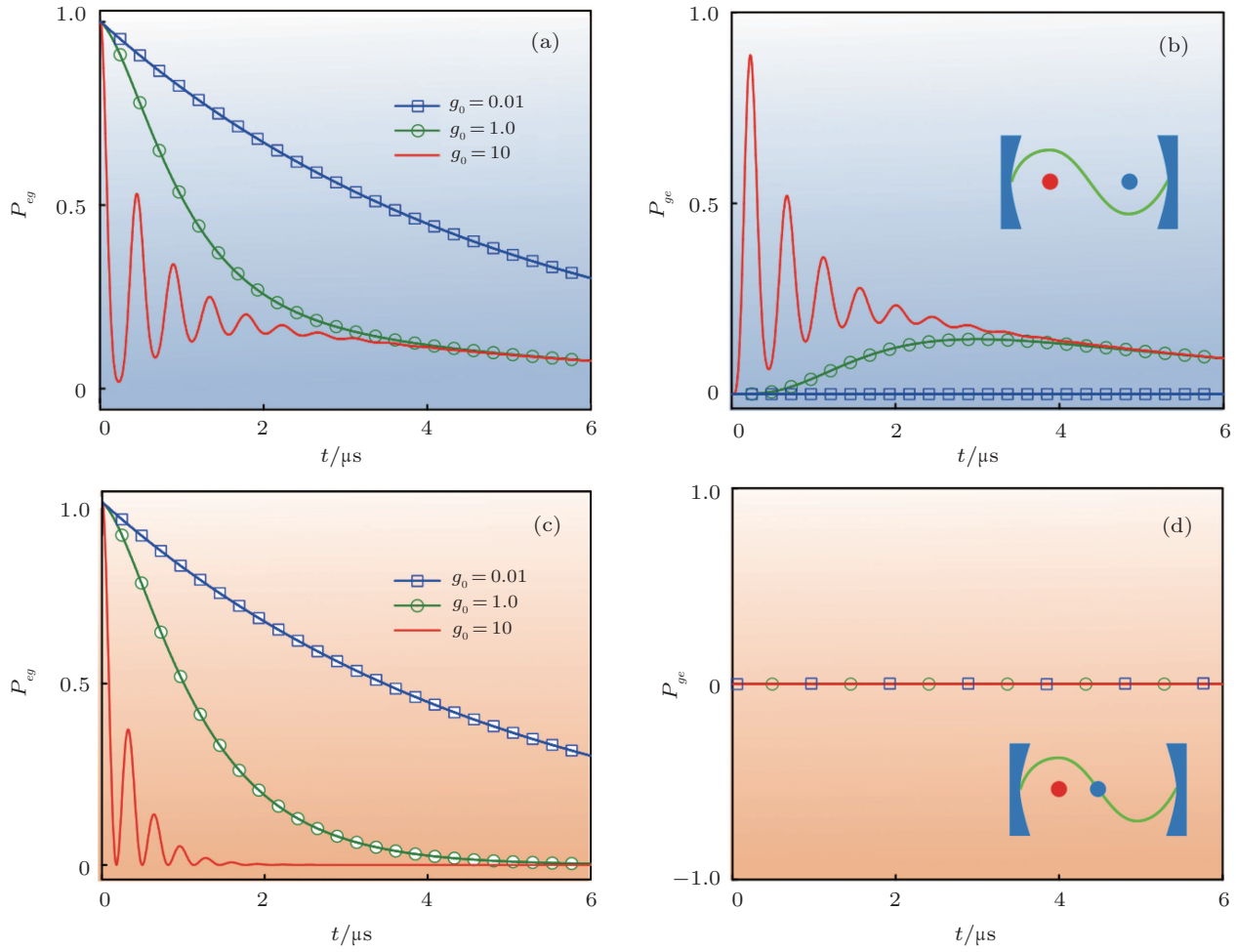


Fig. 5. (color online) The populations in states $|eg\rangle$ [panels (a) and (c)] and $|ge\rangle$ [panels (b) and (d)] with initial conditions of $P_{eg}(0) = 1$ and $P_{ge}(0) = 0$. Here, $\phi_z = 0$ for the top two panels, but $\phi_z = \pi/2$ for the button ones. The coupling strength is chosen as $g_0 = 0.01$ (blue curve), $g_0 = 1$ (green curve), and $g_0 = 10$ (red solid curve). Other system parameters are the same as those in Fig. 2.

4. Conclusion

We have shown that the behavior of the atomic collective decay significantly changes with the phase between the two atoms trapped in a high damping cavity. This arises from the quantum interference between Dicke states. We found that in the case of in-phase or out-phase radiation, the speeding up of the collective decay occurs due to the constructive quantum interference, no matter which atom is excited initially. In the case of $\pi/2$ phase, the speeding up of the collective decay can also be observed if the first atom is excited initially. Although in this case the second atom does not couple to the cavity, the constructive interference still exists and results in an enhanced decay rate of the Dicke state. However, the speeding up of the collective decay disappears due to the destructive quantum interference if the second atom is excited at the beginning. In addition, the speeding up of the collective decay can be significantly enhanced in the strong coupling regime for the $\pi/2$ phase. The study presented here is helpful to understand the nature of the speeding up of the collective decay in cavity quantum electrodynamics, and provide an effective method to control the collective decay via quantum interference effect.

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