Effect of atomic initial phase difference on spontaneous emission of an atom embedded in photonic crystal*

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We investigate the effect of initial phase difference between the two excited states of a V-type three-level atom on its steady state behaviour of spontaneous emission. A modified density of modes is introduced to calculate the spontaneous emission spectra in photonic crystal. Spectra in free space are also shown to compare with that in photonic crystal with different relative positions of the excited levels from upper band-edge frequency. It is found that the initial phase difference plays an important role in the quantum interference property between the two decay channels. For a zero initial phase, destructive property is presented in the spectra. With the increase of initial phase difference, quantum interference between the two decay channels from upper levels to ground level turns to be constructive. Furthermore, we give an interpretation for the property of these spectra.

Keywords: initial phase difference, spontaneous emission spectrum, quantum interference

PACC: 3200, 3270, 4250

1. Introduction

Control of spontaneous emission in multi-level atoms has attracted substantial attention in quantum optics. Considerable effort has been devoted to investigating the effect of surrounding environment and the parameters of applied field on spontaneous emission.[1−7] For instance, phase-dependent effects in spontaneous emission spectra in a Λ-type atom and that for an atom near the edge of a photonic band gap were presented in Refs. [8]–[10]. Spontaneous emission control in a four-level atom was demonstrated theoretically via adjusting the amplitude and phase of the three driving fields.[11] More recently, we treated the influence of both frequency detuning of the external field and photonic band gap on decay property of a tripod atomic system.[12] Moreover, the localized field emitted from degenerate Λ-type atoms in photonic crystals has been studied by Foroozani and coworkers.[13]

It is well known that quantum interference is a basic physical mechanism for modifying atomic spontaneous emission, which leads to unusual phenomena such as coherent population trapping,[14] electromagnetically induced transparency,[15,16] quenching of spontaneous emission,[17] dark line in spectra[18] and spectral-line narrowing[19−21] or cancellation.[22] The effect of a modified reservoir on the nature of the quantum interference in the spontaneous emission of a driven four-level atom has been demonstrated.[23] Moreover, the initial condition of atom especially initial phase difference between the decay channels is a significant parameter determining the quantum interference property of atomic system, which has been noted in a few literatures such as Ref. [24]. However, to our best knowledge no theoretical or experimental work has been carried out to study the effect of initial phase difference on spontaneous emission systematically. In this paper, comparing the spontaneous emission spectra at different relative locations of the upper levels from the upper band-edge in photonic crystal to that in free space, we investigate effects of initial phase difference on quantum interference between the two decay channels from the excited states to the ground state in three-level V-type atoms.

2. Theoretical model

We consider a three-level atom with two excited levels and a single ground level (the well-known V-

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configuration) as shown in Fig. 1.

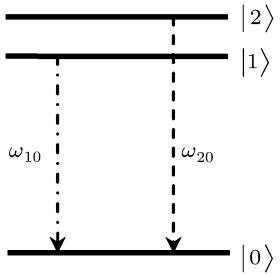


Fig. 1. The V-type atomic system.

Under the rotating wave approximation (RWA), the interaction Hamiltonian for the system can be written as

$$H_{\rm int} = \sum_k g_{1k} {\rm e}^{-{\rm i}(\omega_k-\omega_{10})t} |1\rangle\langle 0| a_k + \sum_k g_{2k} {\rm e}^{-{\rm i}(\omega_k-\omega_{20})t} |2\rangle\langle 0| a_k + {\rm h.c.}, \quad (1)$$

where ω_n is the energy of the atomic level $|n\rangle$ and $\omega_{nm} = \omega_n - \omega_m$ is the energy separation of the states $|n\rangle$ and $|m\rangle$, $a_k(a_k^\dagger)$ represents the annihilation (creation) operator for the k-th vacuum mode with frequency ω_k, g_{1k} and g_{2k} are the coupling constants between the k-th vacuum mode and the atomic transition from $|1\rangle$, $|2\rangle$ to $|0\rangle$, respectively. Here $\hbar = 1$ and real g_{1k}, g_{2k} have been assumed. The atom is initially prepared in a superposition of the two upper levels such that $|\psi(0)\rangle = |a_1(0)| {\rm e}^{{\rm i}\phi_1} |1, \{0\}\rangle + |a_2(0)| {\rm e}^{{\rm i}\phi_2} |2, \{0\}\rangle$, in which $\delta\phi = \phi_2 - \phi_1$ is the initial phase difference of the excited states. The interaction state picture vector of the atomic system at an arbitrary time t can be expressed in terms of bare state vector as

$$|\psi(t)\rangle = a_1(t)|1, \{0\}\rangle + a_2(t)|2, \{0\}\rangle + \sum_k a_k(t)|0, \{k\}\rangle, \quad (2)$$

where k denotes the k-th vacuum mode of the emitted photon and 0 denotes that no photon spontaneously emitted. Making use of the well-known time-dependent Schrödinger equation, the dynamic equations of motion of the probability amplitudes can be found as

$${\rm i}\,\dot{a}_1(t) = \sum_k g_{1k} a_k(t) {\rm e}^{-{\rm i}(\omega_k-\omega_{10})t}, \quad (3a)$$

$${\rm i}\,\dot{a}_2(t) = \sum_k g_{2k} a_k(t) {\rm e}^{-{\rm i}(\omega_k-\omega_{20})t}, \quad (3b)$$

$${\rm i}\,\dot{a}_k(t) = g_{1k} a_1(t) {\rm e}^{{\rm i}(\omega_k-\omega_{10})t} + g_{2k} a_2(t) {\rm e}^{{\rm i}(\omega_k-\omega_{20})t}. \quad (3c)$$

Formally integrating Eq. (3c), and substituting the result into Eqs. (3a) and (3b) to obtain a pair of integro-differential equations

$$\dot{a}_1(t) = -\int_0^t {\rm d}t' \sum_k g_{1k}^2 a_1(t') {\rm e}^{-{\rm i}(\omega_k-\omega_{10})(t-t')} - \int_0^t {\rm d}t' \sum_k g_{1k} g_{2k} a_2(t') \times {\rm e}^{-{\rm i}(\omega_k-\omega_{20})(t-t')} {\rm e}^{-{\rm i}\,\omega_{21} t}, \quad (4a)$$

$$\dot{a}_2(t) = -\int_0^t {\rm d}t' \sum_k g_{2k}^2 a_2(t') {\rm e}^{-{\rm i}(\omega_k-\omega_{20})(t-t')} - \int_0^t {\rm d}t' \sum_k g_{2k} g_{1k} a_1(t') \times {\rm e}^{-{\rm i}(\omega_k-\omega_{10})(t-t')} {\rm e}^{{\rm i}\,\omega_{21} t}. \quad (4b)$$

Considering the case of a single-band isotropic model of the photonic crystal, the dispersion relation near the edge is approximated by $\omega_k = \omega_{\rm c} + \omega_{\rm c}(k - k_0)^2/k_0^2$,[25,26] under which the density of modes reads

$$\rho(\omega) = \frac{1}{\pi} \frac{1}{\sqrt{\omega - \omega_{\rm c}}} \Theta(\omega - \omega_{\rm c}),$$

where Θ is the Heaviside step function and $\omega_{\rm c}$ is the frequency of upper band gap edge. Since the mode density tends to be infinite and presents singularity near the gap edge, we use smoothing parameter ε to eliminate this singularity,[27] and get a modified form of density of modes, expressed as

$$\rho(\omega) = \frac{1}{\pi} \frac{\sqrt{\omega - \omega_{\rm c}}}{\varepsilon + \omega - \omega_{\rm c}} \Theta(\omega - \omega_{\rm c}). \quad (5)$$

Then the kernel function is introduced to simplify Eqs. (4a) and (4b)

$$K_i(t - t') = \sum_k g_{ik}^2 {\rm e}^{-{\rm i}(\omega_k-\omega_{i0})(t-t')} \approx c_i^{3/2} \int {\rm d}\omega \rho(\omega) {\rm e}^{-{\rm i}(\omega_k-\omega_{i0})(t-t')}, \quad (6a)$$

$$K_i'(t - t') = \sum_k g_{1k} g_{2k} {\rm e}^{-{\rm i}(\omega_k-\omega_{i0})(t-t')} \approx (c_1 c_2)^{3/4} \int {\rm d}\omega \rho(\omega) {\rm e}^{-{\rm i}(\omega_k-\omega_{i0})(t-t')}, \quad (6b)$$

where c_i denotes the coupling constants of the atom to the reservoir and $i = 1, 2$. Performing the Laplace transform of Eq. (4) and solving the results directly, the Laplace transform $\tilde{a}_i(s)$ $(i = 1, 2)$ for the amplitudes $a_i(t)$ can be found as

$$a_1(s) = \frac{\left[s + \mathrm{i}\,\omega_{21} + \tilde{K}_2(s + \mathrm{i}\,\omega_{21})\right] a_1(0) - \tilde{K}_2'(s + \mathrm{i}\,\omega_{21}) a_2(0)}{\left[s + \mathrm{i}\,\omega_{21} + \tilde{K}_2(s + \mathrm{i}\,\omega_{21})\right]\left[s + \tilde{K}_1(s)\right] - \tilde{K}_2'(s + \mathrm{i}\,\omega_{21})\tilde{K}_1'(s)}, \tag{7a}$$

$$a_2(s + \mathrm{i}\,\omega_{21}) = \frac{\left[s + \tilde{K}_1(s)\right] a_2(0) - \tilde{K}_1'(s) a_1(0)}{\left[s + \mathrm{i}\,\omega_{21} + \tilde{K}_2(s + \mathrm{i}\,\omega_{21})\right]\left[s + \tilde{K}_1(s)\right] - \tilde{K}_2'(s + \mathrm{i}\,\omega_{21})\tilde{K}_1'(s)}. \tag{7b}$$

Here

$$\tilde{a}_n(s) = \int_0^\infty \mathrm{d}t\, \mathrm{e}^{-st} a_n(t)$$

and

$$\tilde{K}(s) = \int_0^\infty \mathrm{d}t\, \mathrm{e}^{-st} K(t)$$

are Laplace transforms of the atomic amplitude $a_n(t)$ and $K(t)$. Substitute Eq. (5) into Eq. (6) and make Laplace transform then, we obtain the memory kernel functions with $\delta_1 = \omega_{10} - \omega_{\mathrm{c}}$, $\delta_2 = \omega_{20} - \omega_{\mathrm{c}}$,

$$\tilde{K}_1(s) = \frac{c_1^{3/2}}{\mathrm{i}\sqrt{\varepsilon} + \sqrt{\mathrm{i}\,s + \delta_1}}, \tag{8a}$$

$$\tilde{K}_1'(s) = \frac{(c_1 c_2)^{3/4}}{\mathrm{i}\sqrt{\varepsilon} + \sqrt{\mathrm{i}\,s + \delta_1}}, \tag{8b}$$

$$\tilde{K}_2(s + \mathrm{i}\,\omega_{21}) = \frac{c_2^{3/2}}{\mathrm{i}\sqrt{\varepsilon} + \sqrt{\mathrm{i}\,s + \delta_1}}, \tag{8c}$$

$$\tilde{K}_2'(s + \mathrm{i}\,\omega_{21}) = \frac{(c_1 c_2)^{3/2}}{\mathrm{i}\sqrt{\varepsilon} + \sqrt{\mathrm{i}\,s + \delta_1}}. \tag{8d}$$

The long-time spontaneous emission spectrum of this V-configuration in photonic band-gap material can be given by $S(\delta_k) = \rho(\omega_k)\,|a_k(t \to \infty)|^2$, here ω_{c} is the frequency at upper band-gap edge and $\delta_k = \omega_k - \omega_{\mathrm{c}}$. For the sake of convenience, the following change of variables $b_1(t) = a_1(t)$, $b_2(t) = a_2(t)\mathrm{e}^{-\mathrm{i}\,\omega_{21}t}$, $b_k(t) = a_k(t)\mathrm{e}^{-\mathrm{i}(\omega_k - \omega_{10})t}$ was carried out in Eq. (3c). Taking Laplace transform of the result, we have

$$(s + \mathrm{i}\,\delta_{k_1})\tilde{b}_k(s) = -\mathrm{i}\,g_{1k}\tilde{b}_1(s) - \mathrm{i}\,g_{2k}\tilde{b}_2(s), \tag{9}$$

where $\delta_{k1} = \omega_k - \omega_{10}$. Using Eq. (9) and the final value theorem expressed by $f(t \to \infty) = \exp(\mathrm{i}\,\omega t) \times \lim((s - \mathrm{i}\,\omega)F(s))$ as $s \to \mathrm{i}\,\omega$ (for the case where the Laplace transform $F(s)$ has one pole at $s = \mathrm{i}\,\omega$, and all other poles in the left complex s place) the steady state amplitude $b_k(t \to \infty)$ reads

$$b_k(t \to \infty) = \exp(-\mathrm{i}\,\delta_{k1}t) \times \lim_{s \to -\mathrm{i}\,\delta_{k1}} [-\mathrm{i}\,g_{1k}\tilde{b}_1(s) - \mathrm{i}\,g_{2k}\tilde{b}_2(s)], \tag{10}$$

because of $\tilde{b}_2(s) = \tilde{a}_2(a + \mathrm{i}\,\omega_{21})$, we get

$$a_k(t \to \infty) = \lim_{s \to -\mathrm{i}\,\delta_{k1}} [-\mathrm{i}\,g_{1k}\tilde{a}_1(s) - \mathrm{i}\,g_{2k}\tilde{a}_2(s + \mathrm{i}\,\omega_{21})], \tag{11}$$

note that the oscillating factor $\exp(-\mathrm{i}\,\delta_{k1})$is now cancelled out.

We also calculate the spontaneous emission spectra of this V-configuration in free space. Using Weisskopf–Wigner approximation[28,29] in Eqs. (3a) and (3b), the following equations for the probability amplitudes can be found as

$$\dot{a}_1(t) = -\frac{\gamma_1}{2}a_1(t) - p\frac{\sqrt{\gamma_1\gamma_2}}{2}a_2(t)\mathrm{e}^{-\mathrm{i}\,\omega_{21}t}, \tag{12a}$$

$$\dot{a}_2(t) = -\frac{\gamma_2}{2}a_2(t) - p\frac{\sqrt{\gamma_1\gamma_2}}{2}a_1(t)\mathrm{e}^{\mathrm{i}\,\omega_{21}t}. \tag{12b}$$

Here γ_i $(j = 1, 2)$ are the decay rates from the two upper levels to the lower level given by $\gamma_j = |\boldsymbol{\mu}_{j0}|^2 \omega_{j0}^3 / 3\pi\varepsilon_0\hbar c^3$ $(j = 1, 2)$, and $\boldsymbol{\mu}_{j0}$ $(j = 1, 2)$ are the matrix elements of the dipole moments of the two transitions. The parameter p denotes the alignment of the matrix elements of the two dipole moments and is defined as $p = \boldsymbol{\mu}_{20}.\boldsymbol{\mu}_{10} / |\boldsymbol{\mu}_{20}| . |\boldsymbol{\mu}_{10}|$. For orthogonal matrix elements it yields $p = 0$ (no interference) and for parallel elements $p = 1$ (maximum interference). For the simplicity of the following discussion, we assume parallel matrix elements in our system. The spontaneous emission is the Fourier transform of $\langle E^-(t + \tau)\, E^+(t)\rangle_{t \to \infty}$ and can be written as $S(\delta_k) = \gamma_j\,|a_k(t \to \infty)|^2 / 2\pi\,|g_{jk}|^2$ $(j = 1, 2)$. Using the Laplace transform method and the final value theorem, we obtain the spontaneous emission spectrum as follows:

$$S(\delta) \propto \left|\frac{g_{1k}K(\delta) + g_{2k}L(\delta)}{D(\delta)}\right|^2, \tag{13}$$

where $\delta = \omega_k - \omega_{10} - \omega_{12}/2$ is the detuning of the k-th vacuum mode with respect to the central frequency (from the middle point of the two upper levels to the lower level) and

$$K(\delta) = (\delta - \omega_{21}/2 + \mathrm{i}\,\gamma_2/2)a_1(0) - \mathrm{i}\,\frac{\sqrt{\gamma_1\gamma_2}}{2}a_2(0), \tag{14a}$$

$$L(\delta) = (\delta + \omega_{21}/2 + \mathrm{i}\,\gamma_1/2)a_2(0) - \mathrm{i}\,\frac{\sqrt{\gamma_1\gamma_2}}{2}a_1(0), \quad (14b)$$

$$D_1(\delta) = (\delta - \omega_{21}/2 + \mathrm{i}\,\gamma_2/2)(\delta + \omega_{21}/2 + \mathrm{i}\,\gamma_1/2) + \frac{\gamma_1\gamma_2}{4}. \quad (14c)$$

3. Numerical results and discussion

Assuming the initial state of the atom to be $|\psi(0)\rangle = \frac{1}{\sqrt{2}}(\mathrm{e}^{\mathrm{i}\,\phi_1}|1\rangle + \mathrm{e}^{\mathrm{i}\,\phi_2}|2\rangle)$, the effect of initial phase difference $\delta\phi = \phi_2 - \phi_1$ of the upper states on spontaneous emission for atom both in free space and in the photonic crystal is analysed using the analytic expression obtained above. In the free space, as shown in Fig. 2, the spectra are of perfect symmetry and are dramatically influenced by the initial phase difference of the probability amplitudes of the two upper levels. The origin of these spectra features can be attributed to quantum interference due to the existence of the two competitive decay channels from levels $|2\rangle$ and $|1\rangle$ to the ground state $|0\rangle$. In our scheme, as we assume parallel matrix elements of the two transitions, the interference can be constructive or completely destructive depending upon the initial phase difference of the probability of amplitudes of the two upper levels. In the case of $\delta\phi = 0$, the spectrum has two peaks located at $\omega_k = \omega_{10}$ and $\omega_k = \omega_{20}$, respectively and a dark line at $\delta = 0$, which indicates that completely destructive interference between the two decay channels occurs at the zero detuning point. As $\delta\phi$ increases, for example to $\pi/4$, the dark line disappears, and a valley presents the two peaks but the spectrum still shows destructive interference property. With further increase of $\delta\phi$ to $3\pi/4$ and π, two peaks in spectra become closer to each other and the valley between them gets shallower, quantum interference between the two transitions becomes obvious constructive. In fact, quantum interference between the two decay channels always exists as long as there are two close-lying levels with non-orthogonal dipoles in an atomic system, so no matter what initial phase difference is, the spectra are different from the spectra when the dipole moments of the two transition are orthogonal.

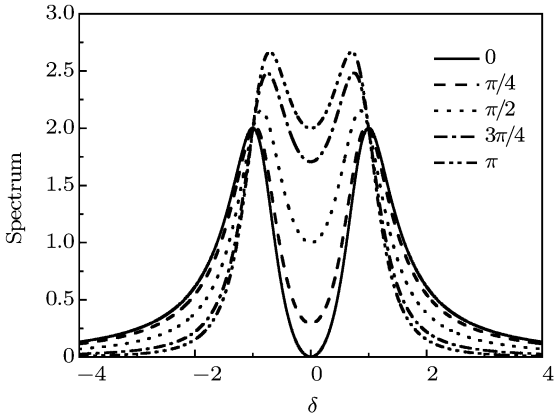


Fig. 2. Spontaneous emission spectra from a V-type three-level atom in free space as a function of the detuning $\delta = \omega_k - \omega_{10} - \omega_{12}/2$, for different initial phase differences $\delta\phi = 0$, $\pi/4$, $\pi/2$, $3\pi/4$, and π.

The spectra of the V-type atomic system in photonic crystal with different relative locations of the excited states from the upper band-edge frequency are shown in Fig. 3 and Fig. 4. Since there is no emission of radiation in the photonic band gap ($\omega_k - \omega_c < 0$), we only give the spectra outside the gap ($\omega_k - \omega_c > 0$) and the emission goes to zero at the photonic band edge ($\omega_k - \omega_c = 0$) as a consequence of the absence of electromagnetic modes at ω_c. As one transition frequency ω_{20} is outside the gap ($\delta_1 > 0$) and the other ω_{10} is at the band edge ($\delta_1 = 0$), it is shown that,

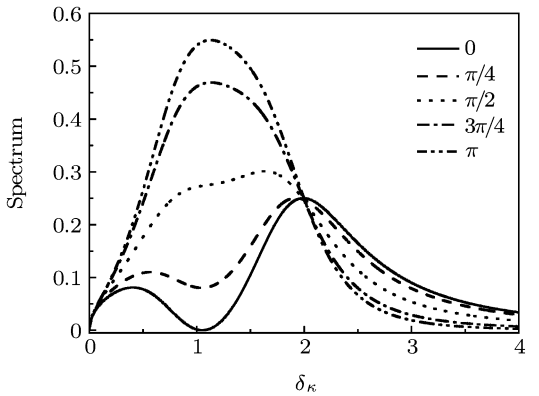


Fig. 3. Spontaneous emission spectra from a V-type three-level atom embedded in photonic crystal versus detuning $\delta_k = \omega_k - \omega_c$ for different initial phase differences when one transition is outside ($\delta_2 = 2$) while the other is at the edge of the gap ($\delta_1 = 0$).

the long time behaviour of radiation is similar to that in the free space except for the asymmetry of the spectral line-shape. In this case, spontaneous emissions in both decay channels are partly depressed, so the

heights of the spectral-lines are reduced and the peak corresponding to the transition near the upper band-gap frequency is much weaker due to the stronger inhibiting effect of the photonic band gap. As $\delta\phi = 0$, destructive interference leads to presence of a dark line in the spectrum. For $\delta\phi$ equals $3\pi/4$ or π, the two peaks merge into one, which indicates the quantum interference between the two decay channels turns to be constructive as $\delta\phi$ increases.

As the position of the upper band-edge further moves to the middle of the two upper levels, which leads to one transition frequency lies in the gap ($\delta_1 < 0$) and the other out of the gap ($\delta_2 > 0$). Since the two transition frequencies are not deep in the band-gap, the quantum interference still exists between the two decay channels. For instance, figure 4 shows the spectra in the case of $\delta_1 = -1$, $\delta_2 = 1$. For a zero initial

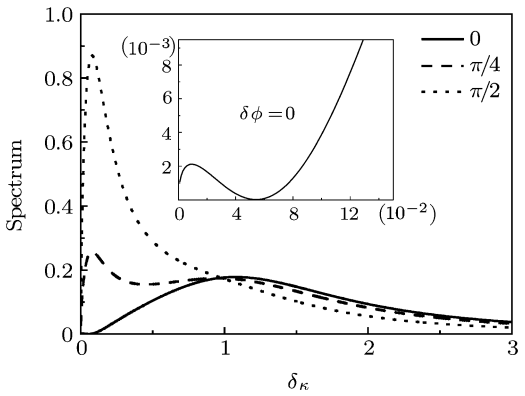


Fig. 4. Spontaneous emission spectra from a V-type three-level atom embedded in photonics crystal versus detuning $\delta_k = \omega_k - \omega_c$ for different initial phase difference one transition is outside ($\delta_2 = 1$) while the other is inside the gap ($\delta_1 = -1$).

phase, with the help of illustration, we see the spectrum is still double peaked but the peak near the photonic band edge ($\omega_k - \omega_c = 0$) is quite small. It is indicated that though one of the transitions lies in the gap and is strongly inhibited, it has effect on the transition outside the gap, which leads to a dark line in spectrum, in other word, the spectrum still shows destructive interference property. As $\delta\phi$ increases to $\pi/4$, we can see only one peak near $\delta = 0$, and with further increase of the initial phase difference, the peak moves to the upper band edge frequency and grows rapidly to an unusual height which is mainly an effect of density of mode.

Since the initial phase difference represents the initial coherent state of the atomic system, an alternative explanation of the properties of these spectra is that as the initial phase difference is zero, the two probability amplitudes are of the same phase, and if one of the transitions happens and populates the ground state it will oppress the other transition and *vice versa*. So the two transitions depress each other and result in destructive interference in the spectra. As the initial phase difference is getting larger, the inhibiting effect between the transitions attenuates and gradually presents constructive interference in the spectra.

4. Conclusion

We investigated the effect of initial phase difference on spontaneous emission spectra of a three-level V-type atom in photonic crystal as well as in free space. The results show that the initial phase difference plays an important role in the atomic spontaneous emission behaviours. As the initial phase difference is zero, the spectra present destructive interference property and when the initial phase difference increases, the quantum interference between two transitions of the atomic system becomes constructive. As both transitions are near the band edge, although the spontaneous emission is partly depressed, the quantum interference between the two decay channels still exists and the nature of which can be modulated by the initial phase difference.

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