Int J Theor Phys (2008) 47: 2554–2565
DOI 10.1007/s10773-008-9689-y

Sudden Death and Long-Lived Entanglement Between Two Atoms in a Double JC Model System

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Received: 11 December 2007 / Accepted: 12 February 2008 / Published online: 21 February 2008

Abstract Considering a double JC model with different coupling constants, we investigate the entanglement between the two two-level atoms, and discuss dependence of the atom-atom entanglement on the different coupling constants, and the detuning between the atomic transition frequency and the cavity field frequency. The results show when $\Delta = \delta/g$ is small, with the increase of the relative difference of the two atom-cavity coupling constants γ, the atom-atom entanglement periodically evolves with the amplitude slowly and periodically modulated. What's more interesting is that long-lived entanglement between the two atoms can be obtained when atom A non-resonantly interacts with the cavity field a, and atom B has no coupling with the cavity field b. In this case, the concurrence $C^{AB}(t)$ of the two atoms evolves in form of cosine, and is invariant and equals the initial value when far off resonance. In addition, we find that the so-called entanglement sudden death can occur under appropriate conditions on the detunings and the different coupling constants for different initial atomic states.

Keywords A double JC model · Entanglement · Sudden death

1 Introduction

Entanglement is one of the most profound features of quantum mechanics and has been recognized as the vital resource for the applications of *quantum computation and quantum communication* [1]. Long-lived qubit entanglement are important prerequisites for realization of quantum information networks [2, 3]. As a result, studying entanglement dynamics

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of qubit pairs in different scenarios is of great importance, and has been the focus of much theoretical and experimental work [4–19]. Brádler et al. have studied the evolution of entanglement for two identical two-level atoms coupled to a resonant thermal field [5]. Observations of entanglement of two remote atomic qubits were reported in reference [4]. Quite recently, Yönac et al. has proposed a double JC model consisting of two two-level atoms labeled A and B, and two cavity modes labeled a and b (A interacting only with a and similarly for B and b) [6–8], and investigated the pairwise entanglement dynamics. They have found, for weak few-photon fields [6, 7], that qubit entanglement is not stationary and can exhibit periodic fluctuations in the form of entanglement sudden death (ESD). However, in their studies, the coupling constants g_i $(i = 1, 2)$ between the atoms and cavities are assumed to be equal, and the field to be at resonance with the atomic transition.

As we know, the coupling constant depends on the atomic position **r** [20]. Due to the randomness of the atomic position **r**, it is very difficult to control the couplings between different atom-cavity systems to be the same. Therefore the study on the random coupling is more significant in experiment. The detuning between the atomic transition frequency and the cavity field frequency, on the other hand, has an effect on entanglement dynamics in various quantum systems [21–27]. Furthermore, the non-resonant atom-cavity system is more conveniently manipulated in experiment than that of exact resonance. In this paper, we consider a double JC model which is similar to that in references [6–8] but with different coupling constants, and that atom A is assumed to not-resonantly interact with a single-mode cavity field a, and atom B to be at one-photon resonance with a single-mode cavity field b. We investigate the entanglement between the two two-level atoms, and discuss dependence of the entanglement on the parameters of the considered system, such as the different coupling constants and the detuning between the atomic transition frequency and the cavity field frequency.

2 The Model

We consider a double JC model with different coupling constants. This model is consisting of two two-level atoms labeled A and B, and two cavity modes labeled a and b (A interacting only with a and similarly for B and b). Atom A not-resonantly interacts with a single-mode cavity field a, and atom B is at one-photon resonance with the single-mode cavity field b. The Hamiltonian of the considered system in the rotating wave approximation and in the interaction picture is (assuming $\hbar = 1$)

$$H_I = g_1(a\sigma_+^A e^{i\delta t} + a^+\sigma_-^A e^{-i\delta t}) + g_2(b\sigma_+^B + b^+\sigma_-^B), \tag{1}$$

where $\sigma_\pm^i$ $(i = A, B)$ are the raising and lowering operators of the ith two-level atom, $a^+(a)$ is the photon creation (annihilation) operator of the cavity mode a, and $b^+(b)$ is that of the cavity mode b. g_1 is the coupling constant between the atom A and the cavity mode a, and g_2 is that between the atom B and the cavity mode b. $\delta = \omega - \nu$ is the detuning between the transition frequency ω of the atom A and the frequency ν of the cavity field a. For the expression of the difference of the two coupling constants, the following transformation is preferable

$$g = \frac{g_1 + g_2}{2}, \quad \gamma = \frac{g_1 - g_2}{g_1 + g_2}, \tag{2}$$

where g denotes average coupling constant, and γ expresses the relative difference of the two atom-cavity coupling constants and is in the range of 0 and 1. After the transformation, The Hamiltonian is rewritten as

$$H_I = g(1+\gamma)(a\sigma_+^A e^{i\delta t} + a^+\sigma_-^A e^{-i\delta t}) + g(1-\gamma)(b^+\sigma_-^B + b\sigma_+^B). \tag{3}$$

We denote by $|e\rangle$ and $|g\rangle$ the excited and ground states of the atoms. Following reference [6], we take the two atoms initially in the Bell-like pure states, and the cavity fields initially in vacuum states $|0\rangle_a \otimes |0\rangle_b = |00\rangle$. Then the two different initial states for the double JC model are

$$|\Psi(0)\rangle = \left(\cos\frac{\theta}{2}|eg\rangle + \sin\frac{\theta}{2}|ge\rangle\right) \bigotimes |00\rangle, \tag{4}$$

and

$$|\Phi(0)\rangle = \left(\cos\frac{\theta}{2}|ee\rangle + \sin\frac{\theta}{2}|gg\rangle\right) \bigotimes |00\rangle, \tag{5}$$

where $0 \le \theta \le \pi/2$.

In the interaction picture solving the Schrödinger equation, we can obtain the time-dependent wave function

$$|\Psi_I(t)\rangle = x_1(t)|eg00\rangle + x_2(t)|ge00\rangle + x_3(t)|gg10\rangle + x_4(t)|gg01\rangle, \tag{6}$$

and

$$|\Phi_I(t)\rangle = y_1(t)|ee00\rangle + y_2(t)|gg00\rangle + y_3(t)|eg01\rangle + y_4(t)|ge10\rangle + y_5(t)|gg11\rangle, \tag{7}$$

where the probability coefficients

$$\begin{aligned}
x_1(t) &= \cos\frac{\theta}{2}\left[\cos\left(\frac{\Omega}{2}gt\right) - i\frac{\Delta}{\Omega}\sin\left(\frac{\Omega}{2}gt\right)\right]\exp\left(i\frac{\Delta}{2}gt\right),\\
x_2(t) &= \sin\frac{\theta}{2}\cos[(1-\gamma)gt],\\
x_3(t) &= -i\frac{2(1+\gamma)}{\Omega}\cos\frac{\theta}{2}\sin\left(\frac{\Omega}{2}gt\right)\exp\left(-i\frac{\Delta}{2}gt\right),\\
x_4(t) &= -i\sin\frac{\theta}{2}\sin[(1-\gamma)gt].
\end{aligned} \tag{8}$$

and

$$\begin{aligned}
y_1(t) &= \frac{\cos\frac{\theta}{2}}{2\Omega\beta\alpha_+\alpha_-}z_1\exp\left(i\frac{\Delta}{2}gt\right),\\
y_2(t) &= \sin\frac{\theta}{2},\\
y_3(t) &= \frac{\cos\frac{\theta}{2}}{2\Omega\beta\xi\alpha_-}z_3\exp\left(i\frac{\Delta}{2}gt\right),\\
y_4(t) &= -i\frac{\cos\frac{\theta}{2}}{\Omega\beta\alpha_+\alpha_-}z_4\exp\left(-i\frac{\Delta}{2}gt\right),\\
y_5(t) &= \frac{(1+\gamma)\cos\frac{\theta}{2}}{\Omega}z_5\exp\left(-i\frac{\Delta}{2}gt\right),
\end{aligned} \tag{9}$$

with

$$
\begin{aligned}
z_1 &= -i\Delta\left[\alpha_+^2 \sin\left(\frac{\alpha_-}{2}gt\right) + \xi\alpha_- \sin\left(\frac{\alpha_+}{2}gt\right)\right] \\
&\quad + \alpha_+\alpha_-[\xi + 2\beta(1-\gamma)]\left[\cos\left(\frac{\alpha_-}{2}gt\right) + \cos\left(\frac{\alpha_+}{2}gt\right)\right], \\
z_3 &= +i\Omega\alpha_+\alpha_-[4(1-\gamma) + \Delta^2 + 8 + 8\gamma^2]\sin\left(\frac{\alpha_+}{2}gt\right) \\
&\quad + \Delta\xi\beta\alpha_- \cos\left(\frac{\alpha_-}{2}gt\right) - \Delta\alpha_-[\Omega\xi + 2\gamma(16-\xi)]\cos\left(\frac{\alpha_+}{2}gt\right) \\
&\quad - i\Omega[4\xi(1-\gamma) + 128\gamma(1+\gamma^2) + \Delta^2(\xi + 8 + 8\gamma^2)]\sin\left(\frac{\alpha_-}{2}gt\right), \\
z_4 &= \alpha_-\xi(1+\gamma)\sin\left(\frac{\alpha_+}{2}gt\right) + \alpha_+^2(1+\gamma)\sin\left(\frac{\alpha_-}{2}gt\right), \\
z_5 &= \cos\left(\frac{\alpha_+}{2}gt\right) - \cos\left(\frac{\alpha_-}{2}gt\right), \\
\alpha_\pm &= \sqrt{\Delta^2 + 8(1+\gamma^2) \pm 4\Omega(1-\gamma)}, \quad \beta = \Omega + 2 - 2\gamma, \quad \xi = \Delta^2 + 16\gamma, \\
\Omega &= \sqrt{\Delta^2 + 4(1+\gamma)^2}, \quad \Delta = \frac{\delta}{g}.
\end{aligned}
\tag{10}
$$

3 The Entanglement Between the Two Two-Level Atoms

Several different measures have been proposed to identify entanglement between two qubits, and we choose the Wootters entanglement measure [28], the concurrence C, defined as

$$C = \max\left(0, \sqrt{\lambda_1} - \sqrt{\lambda_2} - \sqrt{\lambda_3} - \sqrt{\lambda_4}\right) \tag{11}$$

where $\lambda_1, \ldots, \lambda_4$ are the eigenvalues of the matrix $\tilde{\rho} = \rho(\sigma_y \otimes \sigma_y)\rho^*(\sigma_y \otimes \sigma_y)$. ρ is the density matrix representing the quantum state, and the matrix elements are taken with respect to the basis of $|ee\rangle$, $|eg\rangle$, $|ge\rangle$, $|gg\rangle$. The range of the concurrence is from 0 to 1. For unentangled qubits $C = 0$ whereas $C = 1$ for the maximally entangled qubits.

3.1 The Atom-Atom Entanglement for the Initial Atomic State $|\Psi(0)\rangle$

We are only interested in the entanglement dynamics of the two atoms. In order to obtain atom-atom density operator $\rho_I^{AB}(t)$, we trace over the field variables from (6).

For the initial atomic state $|\Psi(0)\rangle$, atom-atom density matrix $\rho_I^{AB}(t)$ written in the basis of $|ee\rangle$, $|eg\rangle$, $|ge\rangle$, $|gg\rangle$ is given by

$$\rho_I^{AB}(t) = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & |x_1(t)|^2 & x_1(t)x_2(t)^* & 0 \\ 0 & x_1(t)^*x_2(t) & |x_2(t)|^2 & 0 \\ 0 & 0 & 0 & |x_3(t)|^2 + |x_4(t)|^2 \end{pmatrix}, \tag{12}$$

the time-dependent matrix elements are given by (8) and (10). The concurrence of the density matrix (12) is expressed by

$$C^{AB}(t) = 2|x_1(t)||x_2(t)|. \tag{13}$$

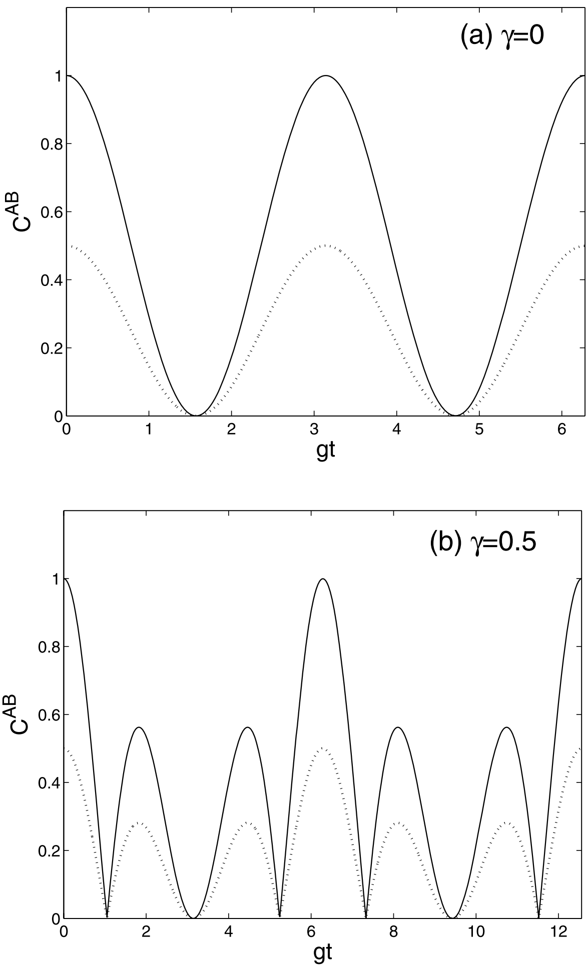
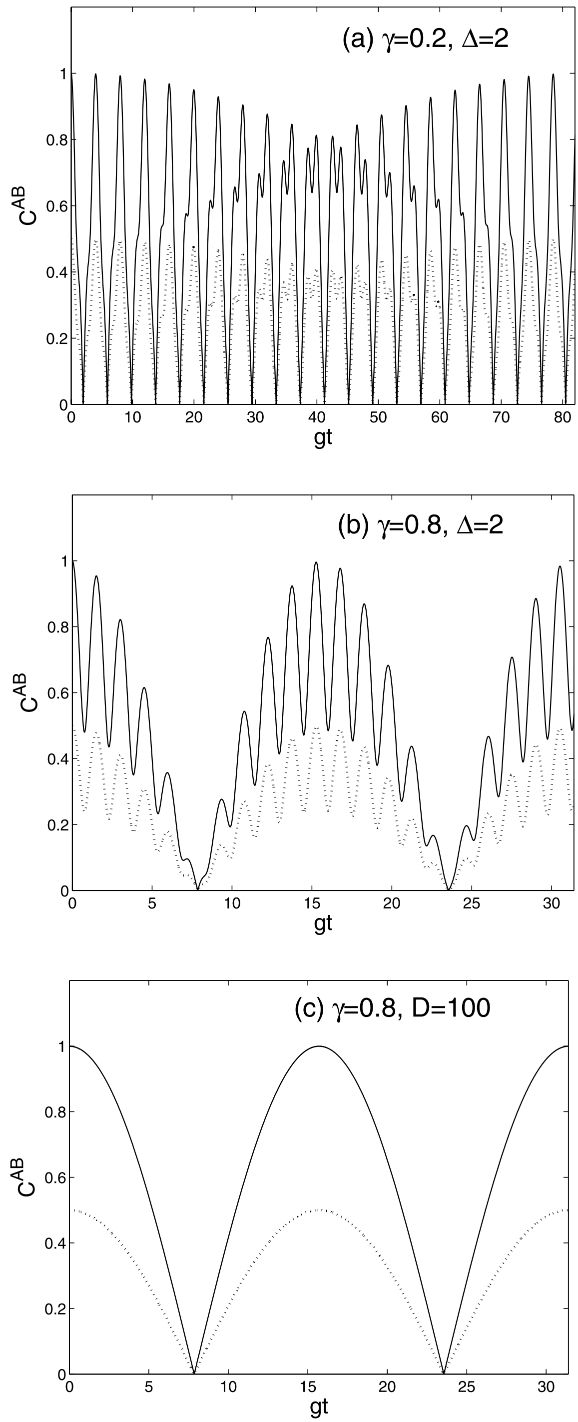


Fig. 1 The time evolution of the concurrence C^{AB} with the initial atomic state $|\Psi(0)\rangle$ when $\Delta=0$ for the different γ, where $\theta=\pi/2$ (*solid*) and $\theta=\pi/6$ (*dotted*)

We plot the time evolution of the concurrence $C^{AB}(t)$ given by (13) for different parameters in Figs. 1, 2 and 3. Figure 1 shows, in the case of exact resonance, the dependence of the concurrence $C^{AB}(t)$ with the initial atomic state $|\Psi(0)\rangle$ on time t and the relative difference of the two atom-cavity coupling constants γ, where $\theta=\pi/2$ by the solid line and $\theta=\pi/6$ by the dotted line. First we consider $\theta=\pi/2$. The entanglement between the two atoms evolves periodically between 0 and 1, but the period is affected by the different coupling constants between the atoms and cavities. It is explained as following. According to (13), the concurrence is expressed by $C^{AB}(t)=\frac{1}{2}\sin(\theta)|[\cos(2gt)+\cos(2\gamma gt)]|$ for $\Delta=0$, which dependence on gt is periodical and the period is the lowest common multiple (LCM) of π and π/γ or half of the LCM.

When atom A interacts with a single-mode cavity field a via not-zero detuning, and atom B is at one-photon resonance with the single-mode cavity field b, $C^{AB}(t)=\sin(\theta)\times$

Fig. 2 The dependence of the concurrence C^{AB} with the initial atomic state $|\Psi(0)\rangle$ on time t, the detuning δ ($\Delta = \delta/g$) and the relative difference of the two atom-cavity coupling constants γ, where $\theta = \pi/2$ (*solid*) and $\theta = \pi/6$ (*dotted*)



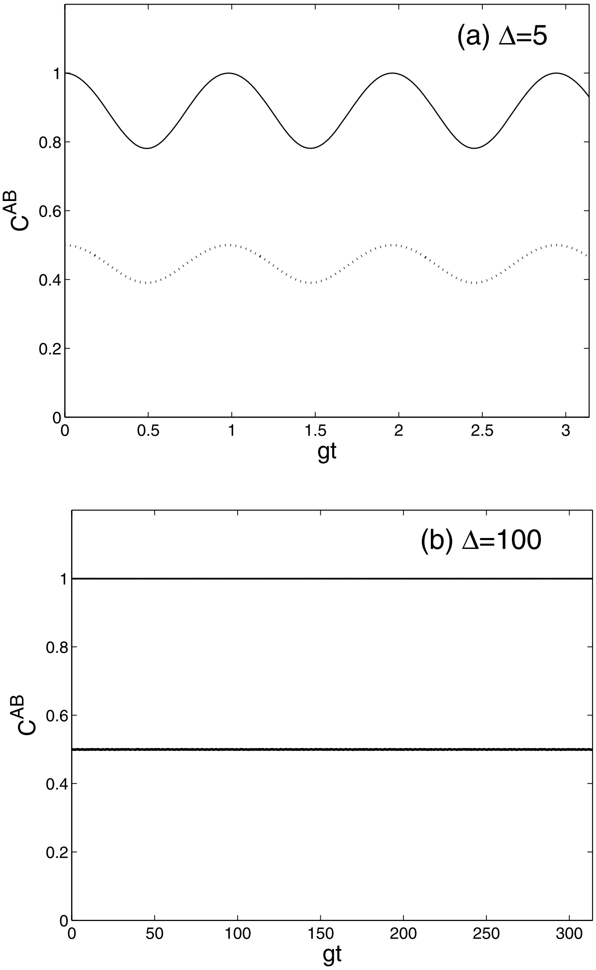


Fig. 3 The time evolution of the concurrence C^{AB} with the initial atomic state $|\Psi(0)\rangle$ when $\gamma = 1$ for $\theta = \pi/2$ (*solid*) and $\theta = \pi/6$ (*dotted*)

$|\cos[(1-\gamma)gt]|\sqrt{\frac{\Omega^2+\Delta^2}{2\Omega^2} + \frac{2(1+\gamma)^2}{\Omega^2}\cos(\Omega gt)}$, the degree of the detuning has great impact on the time evolution of the concurrence $C^{AB}(t)$, as we see in Figs. 2 and 3. And this because the Rabi oscillation frequency Ω is relevant not only to the relative difference of the two atom-cavity coupling constants γ, but also to the detuning between the atomic transition frequency and the cavity field frequency. Let Δ be a small value, we find, firstly, the period of the concurrence $C^{AB}(t)$ is together controlled by the period $\frac{\pi}{1-\gamma}$ of the multiplier $|\cos[(1-\gamma)gt]|$ and that $\frac{2\pi}{\Omega}$ of $\sqrt{\frac{\Omega^2+\Delta^2}{2\Omega^2} + \frac{2(1+\gamma)^2}{\Omega^2}\cos(\Omega gt)}$, which is clearly shown in Fig. 2 for $\theta = \pi/2$ by the solid line and $\theta = \pi/6$ by the dotted line. Secondly, with the increase of γ, it is interesting that the period of the atom-atom entanglement evolution equals $\frac{\pi}{1-\gamma}$, and the amplitude of that is slowly and periodically modulated by $\sin(\theta)\sqrt{\frac{\Omega^2+\Delta^2}{2\Omega^2} + \frac{2(1+\gamma)^2}{\Omega^2}\cos(\Omega gt)}$ (as shown in Fig. 2b), which is similar to "beat" in vibration. Increasing Δ to 100, corresponding to $\delta = 100g$ and $\Omega \approx \Delta$ for any value of γ, which denotes the detuning between the transition frequency of the atom A and the frequency of the cavity field a is much larger than the average coupling constant g, and thus there is no energy exchange between the atom A and the cavity field a. In this case, the concurrence $C^{AB}(t)$ of the two atoms evolves with the period $\frac{\pi}{1-\gamma}$ for $0 \le \gamma < 1$, as we can see in Fig. 2c.

What's more interesting is the time evolution of the atom-atom entanglement for $\gamma = 1$. (This means only atom A interacts with the cavity field a, and atom B has no coupling with the cavity field b.) In this case, long-lived entanglement between the two atoms can be obtained, and the concurrence $C^{AB}(t)$ of the two atoms evolves in form of cosine (as shown in Fig. 3a) with the period $\frac{\pi}{1-\gamma}$ if only Δ is not zero, and is invariant and equals the initial value when far off resonance, which can be clearly seen in Fig. 3b. In addition, from these figures, we note that it is only the amplitude of the atom-atom entanglement evolution which changes for the different parameter θ.

3.2 The Atom-Atom Entanglement for the Initial Atomic State $|\Phi(0)\rangle$

For $|\Phi(0)\rangle$, atom-atom density matrix $\rho_I^{AB}(t)$ is obtained by tracing over the field variables from (7)

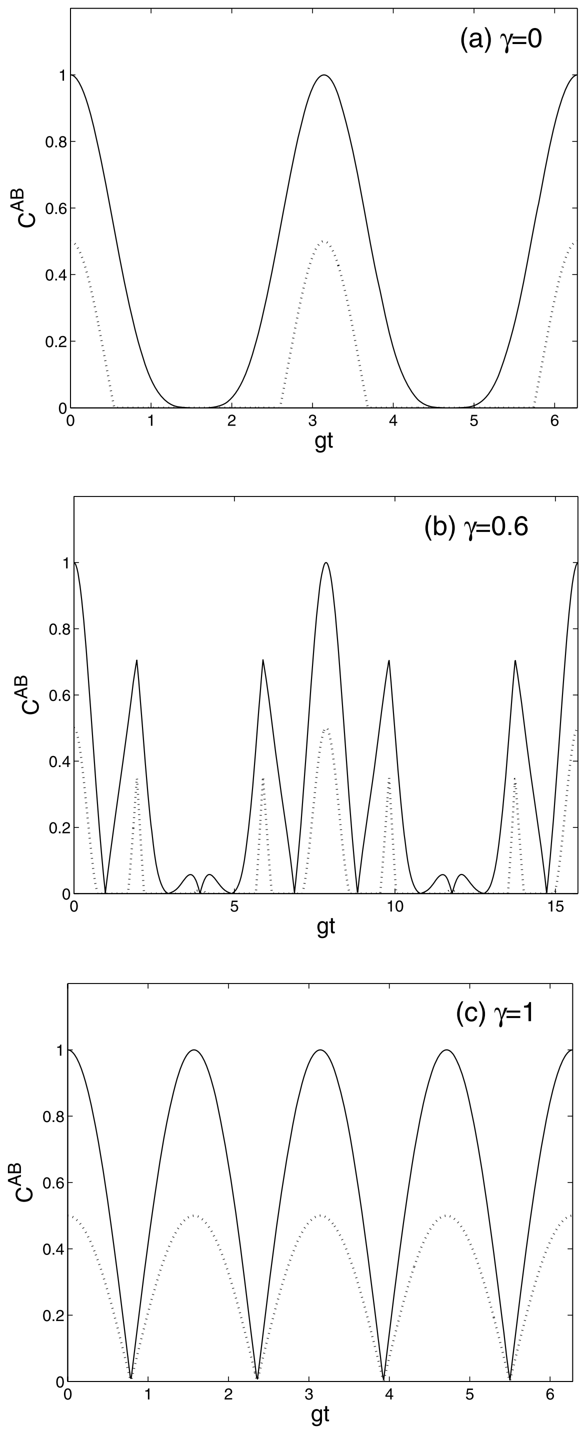
$$\rho_I^{AB}(t) = \begin{pmatrix} |y_1(t)|^2 & 0 & 0 & y_1(t)y_2(t)^* \\ 0 & |y_3(t)|^2 & 0 & 0 \\ 0 & 0 & |y_4(t)|^2 & 0 \\ y_1(t)^*y_2(t) & 0 & 0 & |y_2(t)|^2 + |y_5(t)|^2 \end{pmatrix}, \tag{14}$$

the time-dependent matrix elements are given by (9) and (10). The concurrence for this matrix is

$$C^{AB}(t) = 2\left(|y_1(t)||y_2(t)| - |y_3(t)||y_4(t)|\right). \tag{15}$$

The results for the concurrence $C^{AB}(t)$ with the initial atomic state $|\Phi(0)\rangle$ is illustrated in Figs. 4, 5 and 6, where we can observe the ESD for different values of θ, which differs from that with the initial atomic state $|\Psi(0)\rangle$. It is due to a "dark" state $|gg00\rangle$ in $|\Phi(0)\rangle$, i.e., the state $|gg00\rangle$ is unaffected by coupling to the cavity fields. We let $\Delta = 0$, and discuss the dependence of the atom-atom entanglement on the relative difference of the two atom-cavity coupling constants γ in Fig. 4. For $\gamma = 0$, which means the coupling constant g_1 is equal to g_2, the entanglement can terminate abruptly in finite time (which is so-called ESD), and will remain zero for a period of time before it recovers for any virtual values of θ. But this occurs only for the smaller θ when the coupling constants g_i $(i = 1, 2)$ are different, corresponding to $0 < \gamma < 1$ (in Fig. 4b). When atom A interacts with the cavity field a in the case of resonance, and atom B has no coupling with the cavity field b ($\gamma = 1$), $C^{AB}(t) = \sin\theta|\cos(2gt)|$, there is no longer the ESD for any θ, which can be found in Fig. 4c. In Fig. 5, the relative difference of the two atom-cavity coupling constants $\gamma = 0$, we find the ESD can occur only for small Δ. And at large detunings, the atom-atom entanglement will no longer remain zero for a period of time. When $\gamma \neq 0$ and atom A not-resonantly interacts with a single-mode cavity field a, the two atoms A and B are periodically entangled and disentangled (as shown in Fig. 6a), and the period is affected by the parameters γ and Δ, which is similar to the time evolution of the concurrence $C^{AB}(t)$ for the initial atomic state $|\Psi(0)\rangle$. For $\gamma = 1$ in Fig. 6b, the atom-atom entanglement evolves in the form of cosine and the two atoms do not disentangle if only Δ is not zero. Besides, for far off resonance the concurrence $C^{AB}(t)$ is invariant and equals the initial value for any virtual values of θ.

Fig. 4 The time evolution of the concurrence C^{AB} with the initial atomic state $|\Phi(0)\rangle$ when $\Delta = 0$ for the different γ, where $\theta = \pi/2$ (*solid*) and $\theta = \pi/6$ (*dotted*)



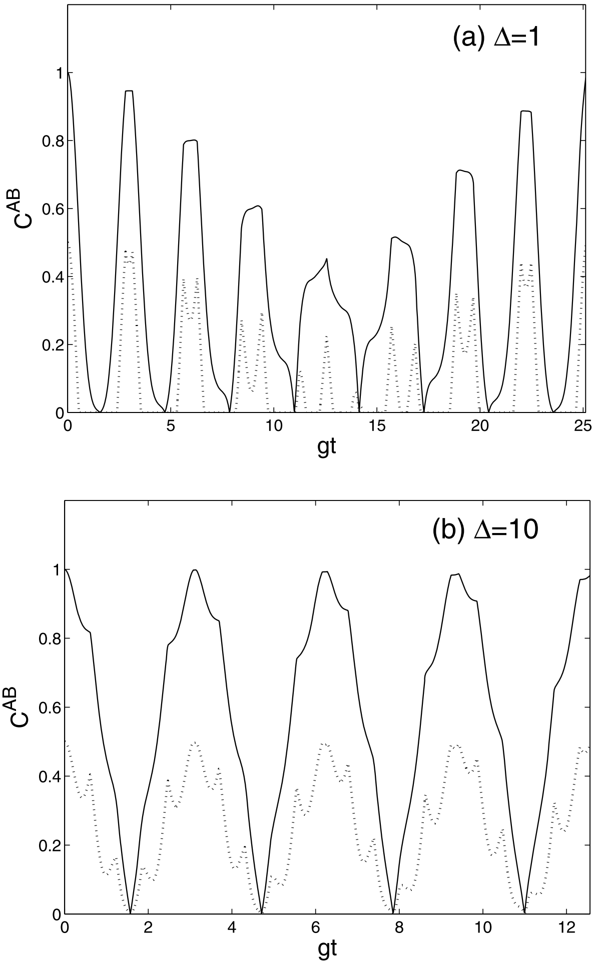
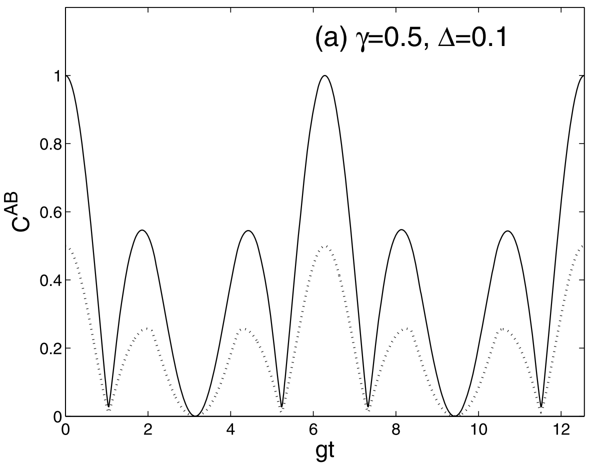


Fig. 5 The dependence of the concurrence C^{AB} with the initial atomic state $|\Phi(0)\rangle$ on time t and the detuning δ ($\Delta = \delta/g$) for $\gamma = 0$, where $\theta = \pi/2$ (*solid*) and $\theta = \pi/6$ (*dotted*)

4 Conclusion

In this paper, we investigate the entanglement between the two two-level atoms in a double JC-model system with different coupling constants, and discuss dependence of the atom-atom entanglement on parameters of the considered system, such as the different coupling constants and the detuning between the atomic transition frequency and the cavity field frequency. The results show these parameters have great impact on the amplitude and the period of the atom-atom entanglement evolution. When $\Delta = \delta/g$ is a small value, with the increase of the relative difference of the two atom-cavity coupling constants γ, the atom-atom entanglement evolves with the period of $\frac{\pi}{1-\gamma}$, and the amplitude slowly and periodically modulated by $\sin(\theta)\sqrt{\frac{\Omega^2+\Delta^2}{2\Omega^2} + \frac{2(1+\gamma)^2}{\Omega^2}\cos(\Omega g t)}$, which is similar to "beat" in vibration. What's more interesting is the time evolution of the atom-atom entanglement for $\gamma = 1$. (This means



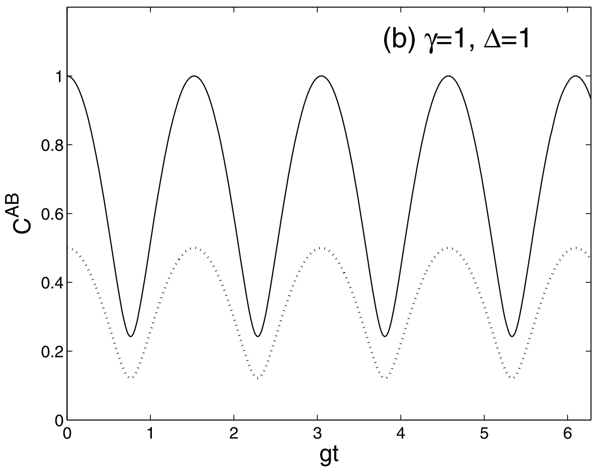


Fig. 6 The dependence of the concurrence C^{AB} with the initial atomic state $|\Phi(0)\rangle$ on time t, the detuning δ ($\Delta = \delta/g$) and the relative difference of the two atom-cavity coupling constants γ, where $\theta = \pi/2$ (*solid*) and $\theta = \pi/6$ (*dotted*)

only atom A interacts with the cavity field a, and atom B has no coupling with the cavity field b.) In this case, long-lived entanglement between the two atoms can be obtained, and the concurrence $C^{AB}(t)$ of the two atoms evolves in form of cosine with the period $\frac{\pi}{1-\gamma}$ if only Δ is not zero, and is invariant and equals the initial value when far off resonance. In addition, we find that the so-called ESD can occur under appropriate conditions on the detunings and the different coupling constants for different initial atomic states. We expect our work will be helpful for studying entanglement dynamics of qubit pairs in practical experiments.

Acknowledgements This work has been financially supported by the National Natural Science Foundation of China (Grant No. 10374025) and the Foundation of Hunan Provincial Education Department of China (Grant Nos. 06A038 and 06C080).

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