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Non-Markovian speedup dynamics control of the damped Jaynes–Cummings model with detuning*

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For a two-level atom in a lossy cavity, a scheme to manipulate the non-Markovian speedup dynamics has been proposed in the controllable environment (the lossy cavity field). We mainly focus on the effects of the qubit–cavity detuning Δ and the qubit–cavity coupling strength κ on the non-Markovian speedup evolution of an open system. By controlling the environment, i.e., tuning Δ and κ, two dynamical crossovers from Markovian to non-Markovian and from no-speedup to speedup are achieved. Furthermore, it is clearly found that increasing the coupling strength κ or detuning Δ in some cases can make the environmental non-Markovianity stronger and hence can lead to faster evolution of the open system.

Keywords: non-Markovianity, quantum speed limits, open system dynamics

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1. Introduction

All realistic quantum systems should be used as an open system due to their unavoidable coupling to uncontrollable environments.[1] Recently, how to understand and control the dynamics of the open quantum system has attracted more and more attention. Generally speaking, the dynamics of the open quantum system must take into account the effects of the environment. The dynamics of this quantum system can be divided into two categories: the Markovian dynamics without the memory effects and the non-Markovian dynamics with the memory effects. To date, many studies have demonstrated that the memory effects of the non-Markovian dynamics of the open system have played an increasingly important role in theory[2–17] and experiments.[18–20] In the process of non-Markovian evolution of the open system, the non-Markovian behavior of the system not only enables the entanglement and coherence of the quantum system to revive[21–23] but also accelerate the quantum evolution speed of the system.[24–29] Besides, it is worth noting that the improvement of the quantum dynamical speed of a quantum system[30] by controlling the non-Markovian effects of the environment is very significant for quantum information processing.[31–39]

So far, for detecting non-Markovian behaviors of open system evolution,[3,7,9,37,40–46] several measure methods have been proposed, such as the Breuer–Laine–Piilo measure based on the distinguishability between different initial states of the system,[9] the Lorenzo–Plastina–Paternostro measure based on the volume of accessible states of the system,[41] and so on.[15] Based on the above measures, the non-Markovian evolution process can absolutely be detected. In Ref. [3], the author analyzed the non-Markovianity of the damped Jaynes–Cummings model with detuning. Recently, a number of people have focused on how to generate non-Markovian dynamics behavior and speedup the dynamics of the quantum system. In Ref. [24], the author considered the damped Jaynes–Cummings model for a qubit resonantly coupling to a leaky single-mode cavity and focused on the non-Markovian effects that could speedup the dynamics process in the strong coupling regime. Then if we consider the damped Jaynes–Cummings model with detuning in the weak-coupling regime, can we acquire the non-Markovian speedup dynamics of the system in the weak coupling regime?

With this question, we mainly study a generic damped Jaynes–Cummings model with detuning of a two-level atom interacting with a lossy cavity. We focus on the effects of detuning Δ and the coupling strength κ on the non-Markovian speedup behaviors of the open system. Here, the Breuer–Laine–Piilo measure[9] is used to describe the Markovian dynamics and non-Markovian dynamics. In order to measure the extent to which the open quantum system accelerates, the quantum speed limit (QSL) time[24,47–54] is used to define the speedup evolutional process. Furthermore, two dynamical crossovers of the quantum system, from Markovian dynamics to non-Markovian dynamics and from no-speedup evolution to speedup evolution, are achieved by manipulating the two parameters, i.e., the qubit–cavity coulping strength κ and the qubit–cavity detuning Δ.

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2. Theoretical method

We investigate a model that the qubit is coupled to a cavity while the cavity is coupled to a Markovian reservoir. The total Hamiltonian is given by ($\hbar = 1$)

$$H = H_{\rm S} + H_{\rm C} + H_{\rm SC} + H_{\rm CR}, \tag{1}$$

where $H_{\rm S} = \omega_{\rm s}\sigma_+\sigma_-$ is the qubit Hamiltonian, $H_{\rm C} = \omega_{\rm c}a^\dagger a$ is the cavity Hamiltonian, $H_{\rm SC} = \kappa(\sigma_+ a + \sigma_- a^\dagger)$ is the interaction Hamiltonian between the qubit and cavity, and $H_{\rm CR} = \sum_k g_k(ab_k^+ + a^\dagger b_k)$ is the interaction Hamiltonian between the cavity and the Markovian reservoir. In the above expression, $a^\dagger$ and a are the creation and annihilation operators for the cavity with frequency $\omega_{\rm c}$, b_k^+ and b_k are the creation and annihilation operators for the k mode of the Markovian reservoir, $\sigma_+ = |e\rangle\langle g|$, $\sigma_- = |g\rangle\langle e|$ and $\omega_{\rm s}$ are the inversion operators and transition frequency of the qubit, κ is the coupling strength between the qubit and the cavity, and g_k is the coupling strength between the cavity and the k mode of the Markovian reservoir. Furthermore, in this paper, we consider that there is a detuning between the frequency of the cavity field mode and the qubit frequency, i.e., $\Delta = \omega_{\rm c} - \omega_{\rm s}$.

We assume that the atom is initially in the excited state and the cavity is in the vacuum state. The evolutional state of the total system takes the form

$$|\phi(t)\rangle = a(t)|1\rangle_{\rm S}|0\rangle_{\rm C} + b(t)|0\rangle_{\rm S}|1\rangle_{\rm C}, \tag{2}$$

where $a(t)$ and $b(t)$ are the probability amplitudes of the qubit and the cavity, respectively. Besides, the probability amplitudes $a(t)$ and $b(t)$ of the system are governed by the Schrödinger equation, from which we can obtain

$$\begin{aligned} {\rm i}\dot{a}(t) &= \kappa b(t) + \omega_{\rm s}a(t), \\ {\rm i}\dot{b}(t) &= \kappa a(t) + \omega_{\rm c}b(t) - ({\rm i}/2)\Gamma b(t). \end{aligned} \tag{3}$$

Then the above equations can be solved by Laplace transform. For convenience, we express the dynamics of the qubit by the reduced density matrix in the system's basis $\{|1\rangle, |0\rangle\}$ as

$$\rho(t) = \begin{pmatrix} \rho_{11}(0)|a(t)|^2 & \rho_{01}(0)a(t)^* \\ \rho_{10}(0)a(t) & \rho_{00}(0) + \rho_{11}(0)(1-|a(t)|^2) \end{pmatrix}, \tag{4}$$

where $\rho_{11}(0) = 1$ and $\rho_{00}(0) = \rho_{10}(0) = \rho_{01}(0) = 0$. The probability amplitude $a(t)$ can be solved to give the exact solution by Laplace transform and inverse Laplace transform, i.e., $a(t) = a(0)g(t)$, where

$$g(t) = {\rm e}^{-\frac{\Gamma t}{4}}\left(\cosh\frac{\Omega t}{4} + \frac{\Gamma + 2{\rm i}\Delta}{\Omega}\sinh\frac{\Omega t}{4}\right)$$

with $\Omega = \sqrt{(\Gamma + 2{\rm i}\Delta)^2 - 16\kappa^2}$.

From the expression of $a(t)$, we try to explore whether the dynamical behavior of the quantum system can be modified by the qubit–cavity detuning Δ, and the coupling strength κ between the atom and the cavity field. In other words, we can change the dynamical behavior of the quantum system by manipulating the dynamical behavior of the cavity field.

3. Non-Markovian dynamics control

In order to further illustrate the roles of the parameters κ and Δ, in what follows we would describe how to tune the cavity field dynamics from Markovian to non-Markovian by manipulating the qubit–cavity coupling strength κ and the qubit–cavity detuning Δ. A general measure $N(\Phi)$ for non-Markovianity, which can be used to distinguish the Markovian dynamics and the non-Markovian dynamics of the quantum system, has been defined by Breuer *et al.*[9] For a quantum process $\Phi(t)$, $\rho^{\rm s}(t) = \Phi(t)\rho^{\rm s}(0)$, where $\rho^{\rm s}(0)$ and $\rho^{\rm s}(t)$ denote the density operators at time $t = 0$ and at any time $t > 0$ of the quantum system, respectively, then the non-Markovianity $N(\Phi)$ is quantified by

$$N(\Phi) = \max_{\rho^{\rm s}_{1,2}(0)} \int_{\sigma>0} {\rm d}t\,\sigma[t, \rho^{\rm s}_{1,2}(0)], \tag{5}$$

with $\sigma[t, \rho^{\rm s}_{1,2}(0)]$ being the rate of change of the trace distance, and

$$\sigma[t, \rho^{\rm s}_{1,2}(0)] = \frac{\rm d}{{\rm d}t}\mathcal{D}(\rho^{\rm s}_1(t), \rho^{\rm s}_2(t)).$$

The trace distance $\mathcal{D}$ describing the distinguishability between the two states is defined as $\mathcal{D}(\rho^{\rm s}_1, \rho^{\rm s}_2) = \frac{1}{2}\|\rho^{\rm s}_1 - \rho^{\rm s}_2\|$, where $\|M\| = \sqrt{M^\dagger M}$ and $0 \le \mathcal{D} \le 1$, and $\sigma[t, \rho^{\rm s}_{1,2}(0)] \le 0$ corresponds to all dynamical semigroups and all time-dependent Markovian processes, while a process is non-Markovian if there exists a pair of initial states and at certain time t such that $\sigma[t, \rho^{\rm s}_{1,2}(0)] > 0$. That is to say, when $\sigma[t, \rho^{\rm s}_{1,2}(0)] > 0$, the non-Markovianity $N(\Phi) > 0$. However, when $\sigma[t, \rho^{\rm s}_{1,2}(0)] \le 0$, the non-Markovianity $N(\Phi) = 0$. We should take the maximum over all initial states $\rho^{\rm s}_{1,2}(0)$ to calculate the non-Markovianity. In Refs. [3] and [9], by drawing a sufficiently large sample of random pairs of initial states, it is proved that the optimal state pair of the initial states can be chosen as $\rho^{\rm s}_+(0) = (|g\rangle + |e\rangle)/\sqrt{2}$ and $\rho^{\rm s}_-(0) = (|g\rangle - |e\rangle)/\sqrt{2}$. Here, for this optimal state pair, the rate of change of the trace distance can be acquired as $\sigma[t, \rho^{\rm s}_{+,-}(0)] = \partial_t|a(t)|^2$. Then the non-Markovianity of the quantum system dynamics process from $\rho^{\rm s}(0)$ to $\rho^{\rm s}(t)$ can be calculated by $N(\Phi) = \int_0^t(\partial_t|a(t)|^2)|_{>0}\,{\rm d}t$.

First of all, for the case of resonating, i.e., $\Delta = 0$,

$$g(t) = {\rm e}^{-\frac{t\Gamma}{4}}\left(\cosh\left(\frac{\Omega t}{4}\right) + \frac{\Gamma}{\Omega}\sinh\frac{\Omega t}{4}\right),$$

with $\Omega = \sqrt{\Gamma^2 - 16\kappa^2}$. In Ref. [2], the author proposed that the Markovian and non-Markovian regimes can be identified by a critical coupling strength $\kappa_{\rm T} = \Gamma/4$. When $\kappa < \kappa_{\rm T}$ in the weak-coupling regime, the evolution is Markovian. However, when $\kappa > \kappa_{\rm T}$ in the strong-coupling regime, the evolution is non-Markovian. Here, we mainly try to achieve the non-Markovian dynamics behavior of the open quantum system by tuning the environment (the lossy cavity field) in both the weak-coupling and strong-coupling regimes.

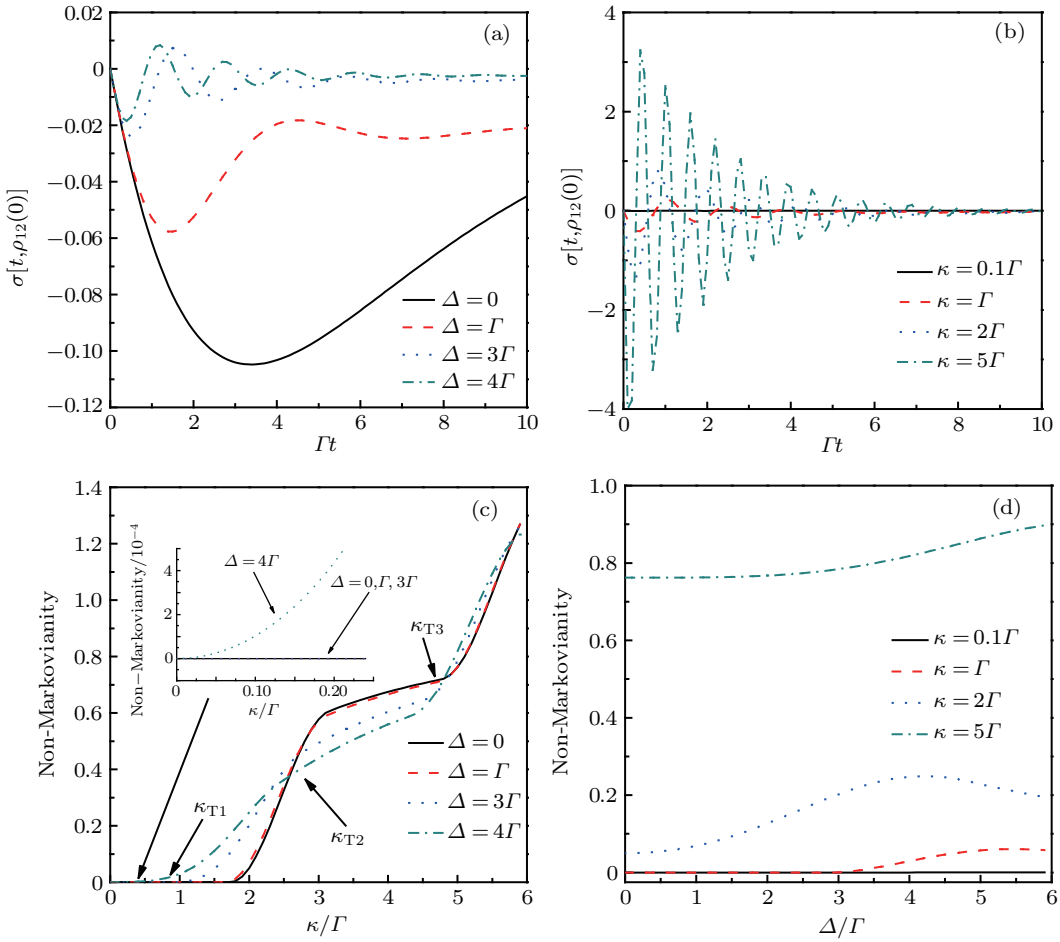


Fig. 1. (color online) (a) and (b) The rate of change of the trace distance $\sigma[t,\rho^{s}_{+,-}(0)]$ as a function of the dimensionless time parameter Γt. (c) and (d) Non-Markovianity $N(\Phi)$ of the atom dynamics process from $\rho^{s}_{0}=|e\rangle\langle e|$ to ρ^{s}_{τ} as a function of the coulping strength κ and the detuning Δ between the qubit and the cavity. The parameters are (a) $\kappa=0.2\Gamma$; (b) $\Delta=4\Gamma$; (c) and (d) $\tau=1$.

To achieve our goal, the rate of change of the trace distance $\sigma[t,\rho^{s}_{+,-}(0)]$ with respect to the dimensionless time parameter Γt for different Δ or κ is plotted in Figs. 1(a) and 1(b), respectively. By fixing $\kappa=0.2\Gamma$ in Fig. 1(a), for the case of resonating, i.e., the solid-black line for $\Delta=0$, the Markovian behavior of the quantum system could always appear in the weak-coupling regime. However, if the qubit and the cavity is detuning, i.e., $\Delta\neq 0$, in the case $\Delta=3\Gamma,4\Gamma$, $\sigma[t,\rho^{s}_{+,-}(0)]>0$ would appear in the dynamics process, as shown in Fig. 1(a). In other words, the non-Markovian dynamics of the open quantum system could be acquired with increasing detuning Δ. Similarly, by fixing $\Delta=4\Gamma$ in Fig. 1(b), for the case of $\kappa=0.1\Gamma$, the Markovian dynamic of the open system would occur in the weak-coupling regime. However, for the case of $\kappa=\Gamma,2\Gamma,5\Gamma$ in Fig. 1(b), $\sigma[t,\rho^{s}_{+,-}(0)]>0$ would occur at a certain time in the strong-coupling regime. That is to say, by fixing the value of $\Delta=4\Gamma$, the non-Markovian dynamics of the quantum system could be acquired with the increase of the coupling strength κ. So it is interesting to find that the dynamical behavior of the quantum system can be controlled by tuning the parameters of the whole system in both the weak-coupling regime and the strong-coupling regime.

Next, we focus on how to manipulate the non-Markovianity of the quantum system. In Ref. [3], the authors considered the case with qubit–reservoir detuning and acquired the non-Markovian behavior of the quantum system by controlling the qubit–reservoir detuning Δ and the spectral width λ of the reservoir. In the following, we also acquire the non-Markovian dynamics behavior of the quantum system by tuning the qubit–cavity detuning Δ and the qubit–cavity coupling strength κ. In Figs. 1(c) and 1(d), we show how to manipulate the non-Markovianity of the quantum dynamics process by the qubit–cavity detuning Δ and the qubit–cavity coupling strength κ. In the inset of Fig. 1(c), there exists a critical detuning Δ_{c}. When $\Delta<\Delta_{c}$, in the case $\Delta=0,\Gamma,3\Gamma$, the dynamics process abides by Markovian behavior. However, when $\Delta>\Delta_{c}$, in the case $\Delta=4\Gamma$, the non-Markovianity monotonically increases with increasing κ. It is worth noting that the dynamical crossover from Markovian behavior to non-Markovian behavior ($\rho_{s}(0)\rightarrow\rho_{s}(\tau)$) can occur at a critical qubit–cavity coupling strength κ_{T1} in Fig. 1(c). When $\kappa<\kappa_{T1}$, the dynamics process abides by Markovian behavior and then the non-Makovianity increases monotonically with increasing κ. Furthermore, when $\kappa_{T1}<\kappa<\kappa_{T2}$ (κ_{T2} is a spe-

cific value of κ), the non-Markovianity increases with increasing detuning Δ. However, when $\kappa_{T2} < \kappa < \kappa_{T3}$ (κ_{T3} is another specific value of κ), the non-Markovianity increases with decreasing Δ. After, the non-Markovianity increases with increasing Δ. In Fig. 1(c), the change of the non-Markovianity indicates that the increase of the detuning not only enhances the non-Markovianity of the quantum system but also weakens the non-Markovianity in some cases. The variation of the non-Markovianity with respect to the detuning Δ for different κ is plotted in Fig. 1(d). It is worth noting that the non-Markovianity increases with increasing κ. In general, we can manipulate the two parameters of the cavity field, i.e., the coupling strength κ and the detuning Δ, to achieve the transform of the quantum system from the Markovian processes to non-Markovian processes.

Finally, in order to further investigate how the qubit–cavity coulping strength κ and the qubit–cavity detuning Δ affect the non-Markovian character of the quantum system, the speed v of the quantum system evolution and the variation rate $\mathrm{d}v/\mathrm{d}t$ of the speed with respect to the coupling-strength κ and the detuning Δ are plotted in Fig. 2. Figures 2(a) and 2(b) show the speed v of the quantum system evolution as a function of κ or Δ at different Δ or κ. It is worth noting that a dynamical crossover from the decelerate to speedup of the quantum system evolution or from the speedup to decelerate of the quantum system evolution can occur at a certain specific value of κ or Δ in Figs. 2(a) and 2(b). In other words, the coupling-strength κ or the detuning Δ can derive the transition between the Markovian dynamics process and non-Markovian dynamics process.

Figures 2(c) and 2(d) show the variation rate $\mathrm{d}v/\mathrm{d}t$ of the speed as a function of κ or Δ. In Fig. 2(c), we can clearly find that the acceleration part ($\mathrm{d}v/\mathrm{d}t > 0$) of the quantum evolution process increases as the detuning Δ increases within certain ranges of coupling strength κ. However, the speedup part ($\mathrm{d}v/\mathrm{d}t > 0$) of the quantum evolution process decreases with increasing detuning Δ in the other ranges of coupling strength κ. Furthermore, the variation rate $\mathrm{d}v/\mathrm{d}t$ of the speed with respect to Δ/Γ for different κ is plotted in Fig. 2(d). It can be seen very clearly that the speedup part ($\mathrm{d}v/\mathrm{d}t > 0$) increases with increasing κ. That is to say, the non-Markovianity becomes stronger with the increase of the coupling-strength κ. Combined with the above analysis, the purpose of the non-Markovian dynamic control can really be achieved by controlling the dynamics of the cavity.

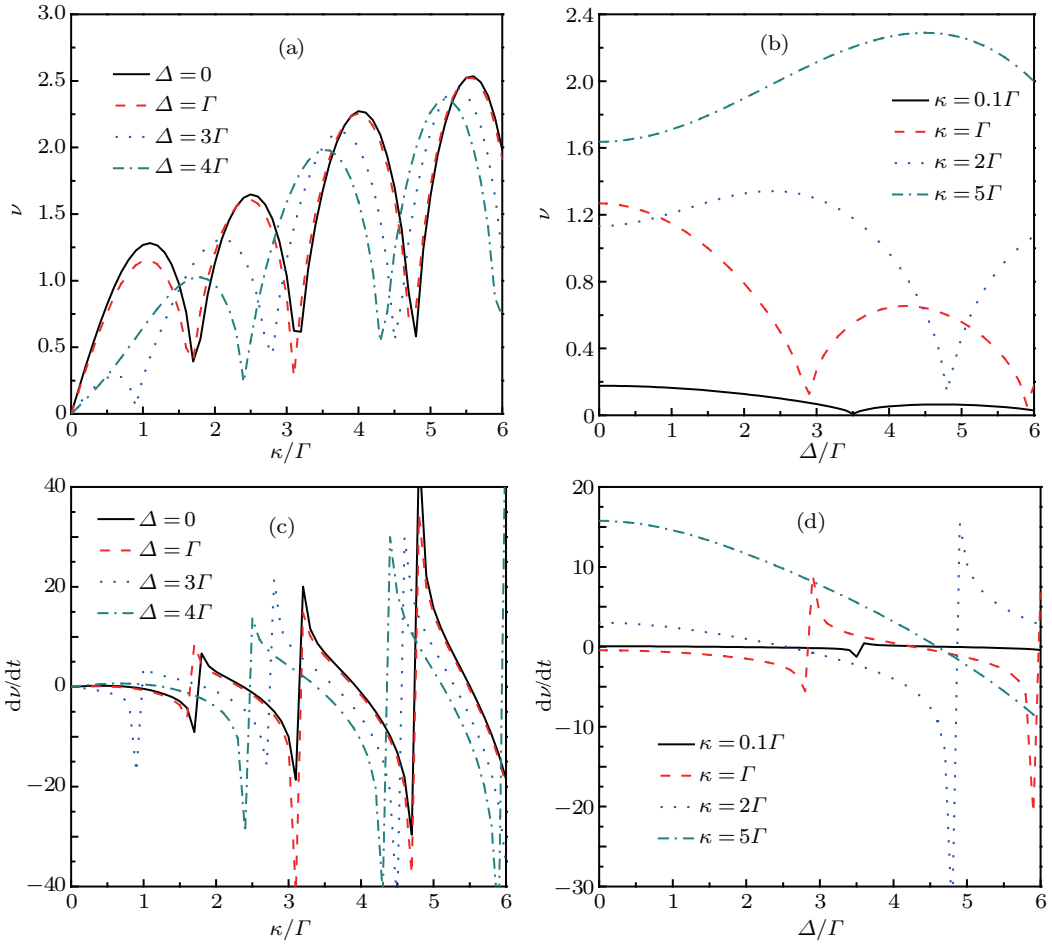


Fig. 2. (color online) (a) and (b) The speed v of the qunatum system evolution as a function of the dimensionless parameter κ/Γ and Δ/Γ. (c) and (d) The variation rate $\mathrm{d}v/\mathrm{d}t$ of the speed of the qunatum system evolution as a function of the dimensionless parameter κ/Γ and Δ/Γ. The parameters are (a) and (c) $\Delta = 0, \Gamma, 3\Gamma, 4\Gamma$; (b) and (d) $\kappa = 0.1\Gamma, \Gamma, 2\Gamma, 5\Gamma$.

4. Quantum speedup dynamics control

Recently, the authors of Refs. [24]–[27] proposed that the non-Markovianity in the dynamics process ($\rho^{s}(0)$ to $\rho^{s}(\tau)$) can lead to faster quantum evolution. In our investigated model, it is easily found that accelerating the evolution of the quantum system can also be achieved by the controllable non-Markovianity discussed above. Then, in this section, we mainly focus on how the qubit–cavity detuning Δ and the qubit–cavity strength coupling κ accelerate the evolution of the quantum system. In order to characterize how fast the quantum system evolves, here we use the definition of the QSL time for an open quantum system,[24] which can be helpful to analyze the maximal speed of the evolution of an open quantum system. The QSL time between an initial state $\rho^{s}(0)=|\phi_0\rangle\langle\phi_0|$ and its target state $\rho^{s}(\tau)$ for an open system is defined as $\tau_{\rm QSL}=\sin^2[B(\rho^{s}(0),\rho^{s}(\tau))]/\Lambda_{\tau}^{\infty}$, where

$$B(\rho^{s}(0),\rho^{s}(\tau))=\arccos\sqrt{\langle\phi_0|\rho^{s}(\tau)|\phi_0\rangle}$$

denotes the Bures angle between the initial and target states of the quantum system, and $\Lambda_{\tau}^{\infty}=\tau^{-1}\int_0^{\tau}\|\dot{\rho}^{s}(t)\|_{\infty}{\rm d}t$ with the operator norm $\|\dot{\rho}^{s}(t)\|_{\infty}$ equaling to the largest singular value of $\dot{\rho}^{s}(t)$. When the ratio between the QSL time and the driving time equals one, i.e., $\tau_{\rm QSL}/\tau=1$, the quantum system evolution is already along the fastest path and possesses no potential capacity for further quantum speedup. While for the case $\tau_{\rm QSL}/\tau<1$, the speedup evolution of the quantum system may occur, and the shorter the $\tau_{\rm QSL}/\tau$, the greater the capacity for potential speedup will be.

In the following, by considering the dynamics process in which the cavity field starts in the excited state $\rho^{s}(0)=|e\rangle\langle e|$, we discuss how the coupling strength κ and the detuning Δ influence the non-Markovian speedup of the cavity field evolution process from $\rho^{s}(0)$ to the target state $\rho^{s}(\tau)$ with the actual evolution time τ. In Fig. 3, we depict the QSL time $\tau_{\rm QSL}/\tau$ as a function of κ or Δ, where the transtion from no speedup to speedup is clearly shown. From Fig. 3(a), in the case $\Delta=0$, Γ, 3Γ, we can clearly find that there exists a critical coupling strength $\kappa_{\rm T}$. When $\kappa<\kappa_{\rm T}$, $\tau_{\rm QSL}$ is equal to the evolution time τ. However, when $\kappa>\kappa_{\rm T}$, $\tau_{\rm QSL}/\tau$ is always less than one. In other words, the non-Markovian speedup behavior of the quantum system can occur. Furthermore, while $\Delta=4\Gamma$ in Fig. 3(a), the QSL time is always less than the actual evolution time τ with increasing coupling strength κ. That is to say, the non-Markovian speedup behavior of the quantum system can always be acquired. Then a remarkable phenomenon in Fig. 3(b) appears when κ is not large enough, $\tau_{\rm QSL}$ would have a sudden transform from $\tau_{\rm QSL}=\tau$ to $\tau_{\rm QSL}<\tau$ at a certain critical $\Delta_{\rm c}$. When $\Delta<\Delta_{\rm c}$, in the case $\kappa=0.1\Gamma$, Γ, the QSL time is actually the evolution time and then decreases monotonically with increasing detuning Δ. However, when κ is large enough in Fig. 3(b), in the case $\kappa=2\Gamma$, 5Γ, the QSL time decreases with increasing detuning Δ. So it is clearly found that the non-Markovian speedup behavior of the quantum system from $\rho_{\rm s}(0)$ to $\rho_{\rm s}(\tau)$ can be acquired by controlling the two parameters κ and Δ of the environment.

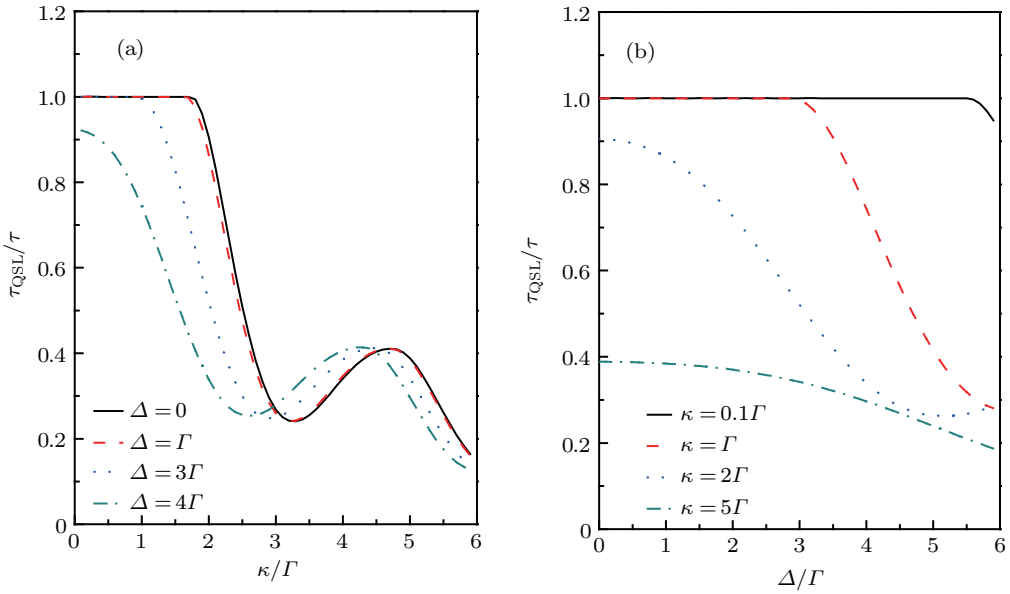


Fig. 3. (color online) The QSL time for the atom dynamic process as a function of the coupling-strength κ and the qubit-cavity detuning Δ. The parameters are (a) $\Delta=0$, Γ, 3Γ, 4Γ; (b) $\kappa=0.1\Gamma$, Γ, 2Γ, 5Γ.

5. Conclusion

In order to achieve the non-Markovian dynamics control of the quantum system, we investigate the generic damped Jaynes–Cummings model with detuning of a two-level atom interacting with a lossy cavity. We investigate the effects of the qubit–cavity detuning Δ and the qubit–cavity coupling strength κ by manipulating the parameters of an adjustable

environment. We find that two dynamical crossovers of the quantum system, from Markovian to non-Markovian dynamics and from no-speedup evolution to speedup evolution, can be achieved by manipulating κ and Δ. Furthermore, we also find that the speed of quantum system evolution can be controlled by tuning κ and Δ. Finally, the non-Markovian speedup dynamics control of the damped Jaynes–Cummings model with detuning can be achieved by controlling the environment (the lossy cavity field).

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