Generation of steady four-atom decoherence-free states via quantum-jump-based feedback*

Wu Qi-Cheng(吴奇成) and Ji Xin(计 新)†

Department of Physics, College of Science, Yanbian University, Yanji 133002, *China*

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A scheme is presented for generating steady four-atom decoherence-free states via four atoms with the Raman level configuration interacting with a single-mode vacuum cavity field by using quantum-jump-based feedback. The scheme meets the condition of a strongly dissipative cavity easily and has a simplified feedback control. Although the spontaneous emission still plays a negative role in the proposed system, we can improve the feedback control to reduce its effect.

Keywords: Raman three-level atom, large detuning, four-atom decoherence-free state, quantum-jump-based feedback

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1. Introduction

It is well known that quantum entanglement lies in the heart of the quantum information theory. It is an important physical resource for quantum information processing (QIP).[1–4] Therefore, much attention has been focused on production and manipulation of entangled states and there have been great advances in the experiment that lead to the realization of entangled states in a variety of physical systems.[5–13] Over the past decades, cavity quantum electrodynamics (QED) has become an important platform for quantum information processing.[14–20] Some experiments, such as the coupling of the trapped atoms with cavity,[21] precisely manipulating the trapped atoms using laser beams and other electromagnetic fields,[22] and real-time monitoring and manipulation of individual quantum systems[23] have been reported. However, even if experiments were to be performed under perfect conditions, decoherence factors such as atomic spontaneous emission and cavity decay are inevitable, limiting the life time of entangled states. Recent studies show that the decoherence-free states were considered as the key solution to the decoherence problem.[24–27] So much attention has been focused on the generation of decoherence-free states in the context of cavity QED.[28–30] In 2000, Beige *et al.* proposed a scheme for generating decoherence-free states with the help of weak laser pulses, using the high decay rate of the cavity field and strong coupling between the atoms and the resonator mode.[28] In 2011, Stevenson *et al.* explored the possibility for controlling entanglement and generating multipartite entanglement using jump-based feedback,[29] and as an example, they prepared a four-qubit decoherence-free state. In 2012, Noguchi *et al.* proposed the generation of entangled states with trapped calcium ions using a combination of an rf dressed state and a spin dependent force.[30] Using this method, they generated a decoherence-free entangled state of rf qubits directly.

Enlightened by the idea of quantum-jump-based feedback,[29,31–35] in this paper, we aim at engineering four-atom decoherence-free states via quantum-jump-based feedback. Similar to the scheme in Ref. [29], our scheme can generate a nearly perfect steady four-atom decoherence-free state from a variety of initial states, which is superior to the schemes of unitary dynamics.[28,30] What is more, compared with the scheme in Ref. [29], our scheme meets the condition of a strongly dissipative cavity easily and simplifies the feedback control, which makes our scheme more feasible for the current experimental techniques.

The paper is organized as follows. In Section 2, we describe the system model and derive the corresponding master equation under the condition of large detuning. In Section 3, we implement the feedback and analyze the influence of feedback coefficients, spontaneous emission, driving field strength, and detection inefficiency on the target state fidelity. In Section 4, experimental feasibility and a conclusion are given.

2. Model and master equation

We consider the case where four atoms with the Raman level configuration are simultaneously interacting with a single-mode vacuum cavity field, as shown in Fig. 1. Each atom includes two ground states labelled as $|0\rangle$ and $|1\rangle$, and an excited state $|2\rangle$. The transition between the levels $|0\rangle_i \leftrightarrow |2\rangle_i$ are coupled to cavity mode a detuned from resonance by Δ, with the coupling constant g_i'. The transition $|1\rangle_i \leftrightarrow |2\rangle_i$ is driven by the classical pulse detuned from resonance by $\Delta+\delta$, with the Rabi frequency Ω_i. The transition $|0\rangle_i \leftrightarrow |1\rangle_i$ is

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†Corresponding author. E-mail: jixin@ybu.edu.cn

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pumped using microwaves detuned from resonance by $-\delta$, with coupling strength ω_i. The atom can spontaneously decay from the excited states to the ground states with rates γ_0^i and γ_1^i $(i=1,2,3,4)$, and the cavity mode is damped with rate κ. For the sake of convenience, we assume $g_i'=g', \Omega_i=\Omega$, $\gamma_{0(1)}^i=\gamma'$, and $\omega_i=\omega$ to be real. The complete master equation describing dynamics of our system reads[16,31]

$$\dot{\rho}=-\mathrm{i}[H,\rho]+\kappa\mathscr{D}[a]\rho+\sum_{i=1}^{4}\sum_{j=0,1}\gamma_j^i\mathscr{D}[|j\rangle_i\langle 2|]\rho, \tag{1}$$

where H is the Hamiltonian of the system

$$\begin{aligned}H &= \Delta J_{2,2}-\delta J_{1,1}+\Omega(J_{2,1}+J_{1,2})\\ &\quad+\omega(J_{1,0}+J_{0,1})+g'(J_{2,0}a+J_{0,2}a^{\dagger}),\end{aligned} \tag{2}$$

and the superoperator $\mathscr{D}$ acting on an operator c is given by $\mathscr{D}[c]\rho\equiv c\rho c^{\dagger}-(c^{\dagger}c\rho+\rho c^{\dagger}c)/2$. The collective operator $J_{k,k'}$ is defined as $J_{k,k'}=\sum_{i=1}^{4}|k\rangle_i\langle k'|$ $(k,k'=0,1,2)$. In what follows, we will derive an effective master equation under the condition of large detuning $(\Delta\gg\Omega,g',\kappa>\omega)$. By adiabatically eliminating the upper level we obtain effective dynamics given by the Hamiltonian

$$\begin{aligned}H_{\mathrm{eff}} &= \left(\frac{\Omega^2}{\Delta}-\delta\right)J_{1,1}+\omega(J_{1,0}+J_{0,1})\\ &\quad-\frac{g'\Omega}{\Delta}(J_{1,0}a+J_{0,1}a^{\dagger}),\end{aligned} \tag{3}$$

where the term $-g'^2a^{\dagger}aJ_{0,0}/\Delta$ is discarded since the cavity mode spends most of the time in the vacuum state.[16] Note that by choosing the detuning δ appropriately $(\delta=\Omega^2/\Delta)$, the first term can be canceled. In other words, we can consider the system as a two-level system where the transition between the levels $|0\rangle_i\leftrightarrow|1\rangle_i$ is coupled to cavity mode a resonantly with the coupling constant $g=-g'\Omega/\Delta$, assisted by a microwaves field with coupling strength ω_i. As can be seen from Eq. (1), the spontaneous emission is proportional to the population of level $|2\rangle$ which can be calculated as a function of the populations of the other two levels $|0\rangle$, $|1\rangle$ as part of the adiabatic elimination process. This leads to an effective spontaneous emission rate of $\gamma_{\mathrm{eff}}=\Omega^2\gamma'/\Delta^2$ that can be adjusted by changing the detuning of the pump laser and cavity mode.[15,33] The corresponding master equation after eliminating the upper level is

$$\dot{\rho}=\mathscr{L}\rho-\mathrm{i}[g(J_{1,0}a+J_{0,1}a^{\dagger}),\rho]+\kappa\mathscr{D}[a]\rho, \tag{4}$$

where the superoperator $\mathscr{L}$ is defined as

$$\mathscr{L}\rho = -\mathrm{i}\omega[(J_{1,0}+J_{0,1}),\rho]+\sum_{i=1}^{4}\gamma_{\mathrm{eff}}\mathscr{D}[|0\rangle_i\langle 1|\,]\rho. \tag{5}$$

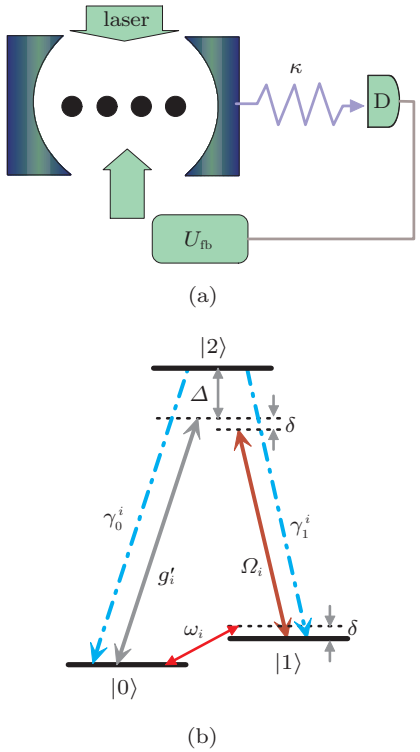


Fig. 1. (color online) (a) Experimental setup containing four atoms trapped inside a heavily damped single-mode cavity and driven by appropriate laser fields. The feedback control is applied to the atoms after the cavity output is measured by a photon detector D. (b) Level configuration of the atoms in the cavity.

Up to now, we find it is easy to meet the conditions of a strongly dissipative cavity $(\kappa\gg g=-g'\Omega/\Delta)$ in the regime of large detuning. So highly excited modes can be neglected safely, and we only need to expand the density matrix ρ in terms of the a mode number states with small photon numbers. So we can obtain the density operator ρ as[32]

$$\begin{aligned}\rho &= \rho_0|0\rangle_a\langle 0|+\rho_1|1\rangle_a\langle 0|+\rho_1^{\dagger}|0\rangle_a\langle 1|+\rho_2|1\rangle_a\langle 1|\\ &\quad+\rho_2'|2\rangle_a\langle 0|-\rho_2'^{\dagger}|0\rangle_a\langle 2|.\end{aligned} \tag{6}$$

Substituting Eq. (6) into Eq. (4), we obtain a set of coupled equations of motion for the field-matrix elements as:

$$\dot{\rho}_0=\mathscr{L}\rho_0-\mathrm{i}g(J_{1,0}\rho_1-\rho_1^{\dagger}J_{0,1})+\kappa\rho_2, \tag{7}$$

$$\dot{\rho}_1=\mathscr{L}\rho_1-\mathrm{i}g(\sqrt{2}J_{1,0}\rho_2'+J_{0,1}\rho_0-\rho_2J_{0,1})-\frac{\kappa}{2}\rho_1, \tag{8}$$

$$\dot{\rho}_2=\mathscr{L}\rho_2-\mathrm{i}g(J_{0,1}\rho_1^{\dagger}-\rho_1J_{1,0})-\kappa\rho_2, \tag{9}$$

$$\dot{\rho}_2'=\mathscr{L}\rho_2'-\mathrm{i}g(\sqrt{2}J_{0,1}\rho_1)-\kappa\rho_2'. \tag{10}$$

Under the condition $\kappa\gg g$, we suppose $\dot{\rho}_1=\dot{\rho}_2'=0$, then substitute the results into Eq. (7) and Eq. (9). After neglecting the terms proportional to second order $O\,(g^2/\kappa^2)$, we can obtain

$$\begin{aligned}\dot{\rho}_0 &= \mathscr{L}\rho_0-\frac{2g^2}{\kappa}(J_{1,0}J_{0,1}\rho_0-2J_{1,0}\rho_2J_{0,1}\\ &\quad+\rho_0J_{1,0}J_{0,1})+\kappa\rho_2,\end{aligned} \tag{11}$$

$$\begin{aligned}\dot{\rho}_2 &= \mathscr{L}\rho_2-\frac{2g^2}{\kappa}(J_{0,1}J_{1,0}\rho_2-2J_{0,1}\rho_0J_{1,0}\\ &\quad+\rho_2J_{0,1}J_{1,0})-\kappa\rho_2.\end{aligned} \tag{12}$$

Solving these two equations and adiabatically eliminating the elements ρ_2, we can obtain the master equation:

$$\dot{\rho} = \mathscr{L}\rho + \Gamma\mathscr{D}[J_{0,1}]\rho, \tag{13}$$

where $\Gamma = 4g^2/\kappa$ is the effective collective decay rate of atoms brought about by large cavity decay. If the rate of $\Gamma/\gamma_{\rm eff}$ is large enough, we can ignore the effect of atomic spontaneous emission, and give the master equation as follows:

$$\dot{\rho} = -\mathrm{i}\omega[(J_{1,0}+J_{0,1}),\rho] + \Gamma\mathscr{D}[J_{0,1}]\rho. \tag{14}$$

This equation describes a system of four atoms with a collective decay channel driven by a classical field. Thus, we have a total of 16×16 linear equations for atoms that do not have a unique steady solution.[36,37] And the decoherence-free state $|D_4\rangle = (2|1100\rangle - |1010\rangle - |0110\rangle - |1001\rangle - |0101\rangle + 2|0011\rangle)/\sqrt{12}$ is a steady state of Eq. (14). In order to obtain the target state $|D_4\rangle$, the local feedback control is introduced after the cavity output is measured by a photon detector D.[31,34,37]

3. Implementations of the feedback

The stochastic master equation describing our current system can be written as

$$\dot{\rho} = -\mathrm{i}\omega[(J_{1,0}+J_{0,1}),\rho] + \Gamma\mathscr{D}[U_{\rm fb}J_{0,1}]\rho, \tag{15}$$

where $U_{\rm fb} = \exp[-\mathrm{i}\lambda(|0\rangle_1\langle 1| + |1\rangle_1\langle 0|) - \mathrm{i}\lambda(|0\rangle_2\langle 1| + |1\rangle_2\langle 0|]$ is a feedback control which is much simpler than that in Ref. [29] and λ corresponds to the intensity of the feedback control. The target state fidelity is defined as $F(|D_4\rangle,\rho) = \sqrt{\langle D_4|\rho|D_4\rangle}$, and we will use it to evaluate the performance for the feedback control. For the sake of convenience, we assumed $\gamma_{\rm eff} = \gamma$. Numerical analysis shows that, without spontaneous emission effects, the four-atom decoherence-free states can be generated from the initial states $|0000\rangle$, $|0011\rangle$, $|1100\rangle$, $|1111\rangle$, respectively, or from their any superposition. The target state fidelity as a function of the feedback and driving strengths from an initial state $|0000\rangle$ is given in Fig. 2(a). Apparently, a nearly perfect four-atom decoherence-free state can be achieved for a wide range of parameters without spontaneous emission effects. However, when spontaneous emission is taken into account, numerical analysis shows that we can generate the four-atom decoherence-free states from any initial state, which shows that the four-atom decoherence-free state is the unique steady state of the system.[36,37] In Fig. 2(b), we plot the time evolution of the target state fidelity versus the effect of different spontaneous emission and all atoms still initially in the ground state. The fidelity drops with the increase of spontaneous emission rate and decay with the increase of time. Consequently, the atomic spontaneous emission is a

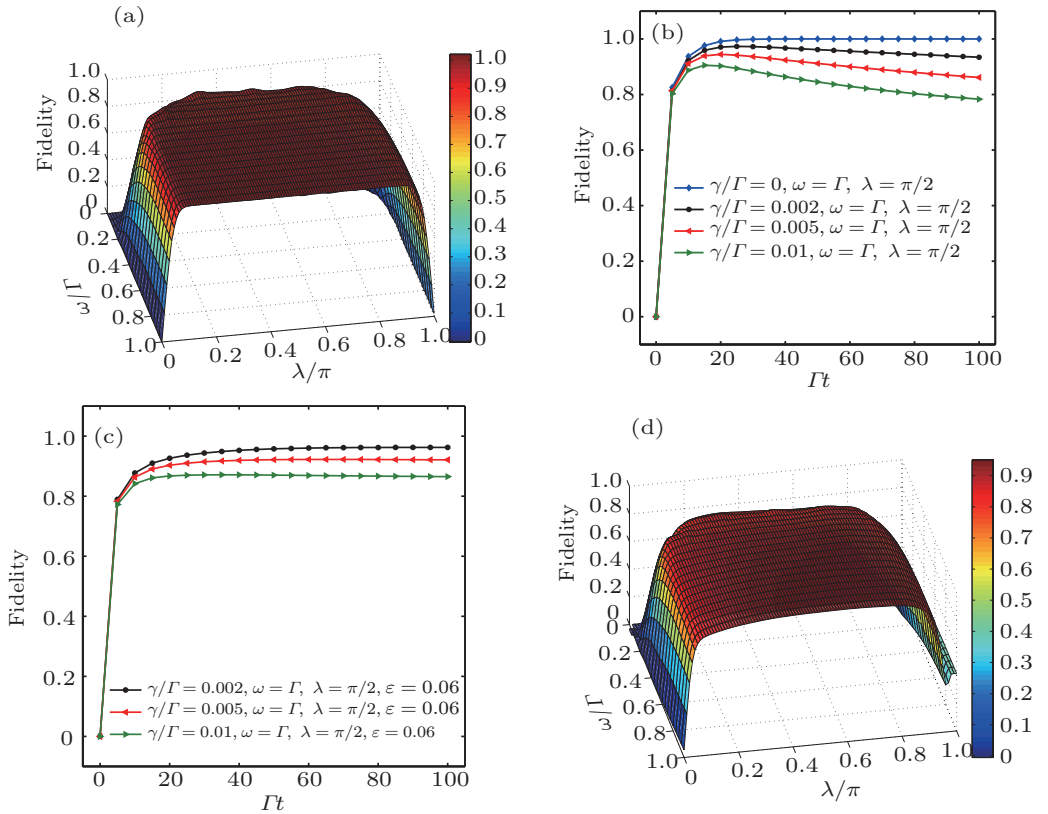


Fig. 2. (color online) (a) The target state fidelity as a function of feedback coefficients and driving strength for local control without spontaneous emission effect. The time evolution of the target state fidelity versus the effect of different spontaneous emission (b) with the feedback control $U_{\rm fb}$ and (c) with the improved feedback control $U_{\rm fb1}$. (d) The target state fidelity as a function of the improved feedback coefficients and driving strength for local control with spontaneous emission effect $\gamma/\Gamma = 0.01$.

detrimental factor for our current model. In order to reduce the effects of spontaneous emission, we introduce a small deviation ϵ from the feedback coefficients.[29] Then the improved feedback control can be written as $U_{\rm fb1} = \exp[-{\rm i}\lambda(|0\rangle_1\langle 1| + |1\rangle_1\langle 0|) - {\rm i}\lambda(1-\varepsilon)(|0\rangle_2\langle 1| + |1\rangle_2\langle 0|) - {\rm i}\lambda\epsilon(|0\rangle_3\langle 1| + |1\rangle_3\langle 0|)]$. After calculation we can find an appropriate ε value ($\varepsilon = 0.06$) to make the improved feedback control reduce the effects of spontaneous emission effectively, as shown in Fig. 2(c). We give the target state fidelity as a function of the improved feedback control and driving strengths with the spontaneous emission effect ($\gamma/\Gamma = 0.002$) in Fig. 2(d). We find the target state also can be achieved for a wide range of parameters with high fidelity.

Until now, we only consider the ideal detection process and neglect the effects of inefficiency of the detector. Taking this element into account, the evolution of the system is governed by the master equation:

$$\begin{aligned}\dot{\rho} &= -{\rm i}\omega[(J_{1,0}+J_{0,1}),\rho] + \eta\Gamma\mathscr{D}[U_{\rm fb1}J_{0,1}]\rho \\ &\quad + (1-\eta)\Gamma\mathscr{D}[J_{0,1}]\rho, \end{aligned} \tag{16}$$

where η stands for the efficiency of the detector. The feedback transformation $U_{\rm fb1}$ is applied after the detector event. Here $(1-\eta)$ corresponds to the case that the detector fails to detect the quantum-jump event and the feedback transformation $U_{\rm fb1}$ is not applied. In Fig. 3, we plot the fidelity of the decoherence-free state versus the effect of different detection efficiencies with $\Omega = \Gamma$, $\lambda = \pi/2$, and all atoms initially in the ground state. Apparently, the system can always reach the decoherence-free state without atomic decay, but the time needed depends on the efficiency of the detection process. In the presence of spontaneous emissions, the final fidelity will decrease with the increase of γ and the decrease of η, which is very consistent with the results in Ref. [16]. In Ref. [16], Metz and Beige elaborated that smaller detector efficiencies required a larger cooperativity parameter (it corresponds to the parameter Γ/γ in our scheme) to obtain a high target state fidelity.

In fact, the correctness of the adiabatic approximation can be described by considering the master equation below:

$$\dot{\rho} = -{\rm i}[H,\rho] + \kappa\mathscr{D}[U_{\rm fb}a]\rho + \sum_{i=1}^{4}\sum_{j=0,1}\gamma_j^i\,\mathscr{D}[|j\rangle_i\langle 2|\,]\rho, \tag{17}$$

which is able to be transformed back to Eq. (15) if the terms that correspond to spontaneous emission are discarded and an adiabatic elimination is performed. Nevertheless, after the introduction of the improved feedback control, we will find that the system is governed by the master equation:

$$\dot{\rho} = -{\rm i}[H,\rho] + \kappa\mathscr{D}[U_{\rm fb1}a]\rho + \sum_{i=1}^{4}\sum_{j=0,1}\gamma_j^i\,\mathscr{D}[|j\rangle_i\langle 2|\,]\rho. \tag{18}$$

Then, in the large detuning regime with $\Delta = 100g$, $\kappa = 4\gamma'$, $\Omega = g' = 10\gamma'$, $\omega = 0.01\gamma'$, and $\lambda = \pi/2$, the fidelity of the steady state is about 0.832, and this result is very consistent with the effective model denoted by the green line with triangles in Fig. 3.

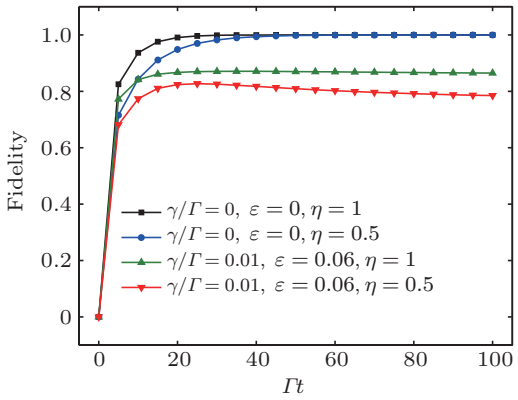


Fig. 3. (color online) The fidelity of four-atom decoherence-free state versus the effect of different detection efficiencies with $\Omega = \Gamma$, $\lambda = \pi/2$ and all atoms initially in the ground state. Without decay the system always reaches the decoherence-free state, with the time depending on the efficiency, while the presence of spontaneous emission results in a decrease in the final fidelity.

4. Experimental feasibility and conclusions

It is necessary to briefly discuss the experimental feasibility of our scheme. The atomic configuration involved in our scheme can be implemented with Cs. As trapping atoms inside a cavity is experimentally feasible, which has already been shown by several groups,[16,22,38,39] we can precisely manipulate the trapped atoms, laser beams, and microwave fields utilizing the techniques proposed in Refs. [22], [38], and [39] to attain the same Rabi frequency and atom–cavity coupling. The feedback control in our scheme follows the principle of violating the symmetry with respect to the exchange of atoms which can be realized with the techniques proposed in Ref. [40]. From an experimental view point, the bad-cavity regime ($\kappa \gg g' \gg \gamma'$) in Ref. [29] is difficult to achieve since the improvement of cavity quality would spoil the condition $\kappa \gg \gamma'$.[31] However, our scheme can meet the condition of a strongly dissipative cavity ($\kappa \gg g = -g'\Omega/\Delta \gg \gamma = \Omega^2\gamma'/\Delta^2$) easily in the regime of large detuning. In recent experiments,[33,41] cavity QED parameters approaching the large detuning regime limit $(\Delta, g', \kappa, \gamma') \sim 2\pi \times (79.6, 10, 0.4, 2.6)$ MHz were acquired. By substituting these parameters into Eq. (18), we obtain fidelity 93.2% in the case of $\Omega = 0.01g'$, $\omega = \Gamma$, and $\lambda = \pi/2$. The value is high for quantum computation especially in the sense of steady-state entanglement.[32]

In conclusion, we have proposed a scheme for generating a steady four-atom decoherence-free state based on quantum-jump-based feedback. This scheme needs a detector to monitor the output of photons from the cavity mode. The effects of

inefficiencies of detection and the atomic spontaneous emissions have been discussed in detail. Moreover, the large detuning regime and simplification of feedback control make our scheme more feasible for the current experimental techniques.

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