Dissipative preparation of a steady three-dimensional entangled state via quantum-jump-based feedback*

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(Received 25 April 2013; revised manuscript received 16 July 2013; published online 24 January 2014)

A robust and scalable scheme to generate a steady three-dimensional entangled state for a V-type atom and a Λ-type atom trapped in a strongly dissipative bimodal cavity is proposed by direct feedback control based on quantum-jump detection. The robustness of this scheme reflects in the insensitivity to detection inefficiencies and the strong ability against the parameter fluctuations in the feedback, driving, and coupling strengths. The influence of atomic spontaneous emission can be suppressed by using the local feedback control. The scalability is ensured that N-dimensional entangled states of two atoms can be deterministically generated.

Keywords: three-dimensional entangled state, quantum jump, feedback control

PACS: 03.67.Bg, 03.65.Yz, 42.50.Lc, 42.50.Dv **DOI:** 10.1088/1674-1056/23/3/030301

1. Introduction

Quantum entanglement, a striking feature distinguished from the classical theory, has been widely used to test fundamental quantum theories and implement quantum computation and quantum communication protocols. Therefore, much effort has been devoted to the preparation of entangled states.[1–6] However, among the existing schemes, most are about two-dimensional entangled states between qubits in Hilbert spaces. Recently, many studies revealed that high-dimensional systems have many significant advantages over two-dimensional systems for some certain tasks. For example, violations of local realism in qudit systems are stronger than that in qubit systems[7] and Greenberger–Horne–Zeilinger paradoxes have also been generalized to d-dimensional ($d \geq 3$, i.e., qudit) systems.[8] In addition, for communication high-dimensional entanglement allows more information to be transmitted, which is shared by the same number of particles. Quantum key distribution encoding in qudit systems is more secure against certain types of eavesdropping attacks.[9,10]

The generation of high-dimensional entangled states attracts much interest owing to their extended possibilities. Experiments aiming to create photonic high-dimensional entanglement in orbital angular momentum have been reported.[11–13] At present, the production of high-dimensional entangled states in theory is mainly based on cavity quantum electrodynamics systems via unitary dynamics evolution,[14–18] adiabatic passage,[19–23] or Zeno dynamics.[24,25] Nevertheless, as we all know, a quantum system inevitably exhibits decoherence due to the coupling with its environment, so it remains a challenge to generate steady high-dimensional entangled states.

Quantum feedback control is regarded as a promising approach to deal with the decoherence problem and prevent entanglement degradation with the development of experiments and theories about monitoring systems in the real time and manipulating individual quantum systems.[26–33] Steady bipartite and multipartite two-dimensional entanglement has been prepared via direct feedback under appropriate detection strategies.[34–38] Furthermore, the nearly perfect three-atom singlet state was also engineered via quantum-jump-based feedback.[39] Current research shows that the asymmetric feedback with respect to exchange of particles based on quantum-jump detection is very useful for engineering steady highly entangled states.

In this work, we propose a scheme to prepare a steady entangled state of two qutrits by feedback control with the help of quantum jump. Based on quantum feedback, the present scheme has the following advantages: (i) It needs neither atomic state initialization nor strict control of the interaction time. The system is deterministically driven to the steady target entangled state. (ii) In our scheme, cavity decay is helpful for the generation of the steady state. This scheme is insensitive to detection inefficiencies and robust against the parameter fluctuations. (iii) It can be generalized to the preparation of bipartite multi-dimensional entangled states.

2. Basic model and effective dynamics for atoms

We consider a system consisting of a V-type atom A and a Λ-type atom B which couple resonantly to a damped bimodal

*Project supported by the National Natural Science Foundation of China (Grant Nos. 61068001 and 11264042), the Postdoctoral Science Foundation of China (Grant No. 2012M520612), and the Talent Program of Yanbian University of China (Grant No. 950010001).

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cavity and are simultaneously driven by two classical fields. Atom A has two degenerate excited states labeled as $|1\rangle$ and $|2\rangle$ and a ground state labeled as $|0\rangle$. On the contrary, atom B has an excited state $|0\rangle$ and two degenerate ground states $|1\rangle$ and $|2\rangle$. The transition between the levels $|1\rangle_j \leftrightarrow |0\rangle_j$ ($|2\rangle_j \leftrightarrow |0\rangle_j$ ($j = A, B$)) is coupled to the left (right) circular polarized mode a_1 (a_2) of the cavity with the coupling constant g_1 (g_2), driven by a classical field with the Rabi frequency Ω_1 (Ω_2), as shown in Fig. 1. The detection apparatus D is used to detect the photons leaking from one of the cavity mirrors. When the detector clicks, one immediately imposes a finite amount of evolution on the atoms by using control lasers or microwaves. The feedback operators could be designed, in theory, as any unitary transformation. Nonetheless, experimentally a reasonable example is a microwave pulse applied to one or more atoms because of the limitation of the technique. Specific feedback operators are shown below.

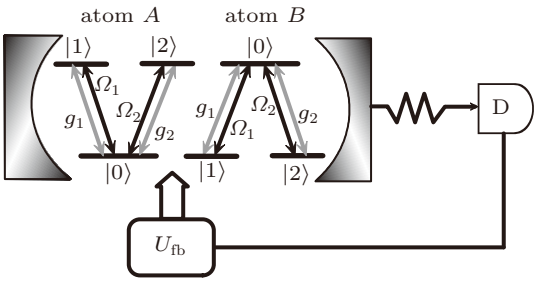


Fig. 1. Schematic view of the model. A V-type atom and a Λ-type atom are trapped in a double-mode cavity. When a photon from the leaky cavity is detected by a detection apparatus, a feedback pulse is triggered.

The complete master equation governing the dissipative dynamics of the whole system reads

$$\begin{aligned}\dot{\rho} =& -\mathrm{i}\Omega_1[(J_1^+ + J_1^-),\rho] - \mathrm{i}\Omega_2[(J_2^+ + J_2^-),\rho] \\ & - \mathrm{i}g_1[(J_1^+ a_1 + J_1^- a_1^\dagger),\rho] - \mathrm{i}g_2[(J_2^+ a_2 + J_2^- a_2^\dagger),\rho] \\ & + \kappa_{a_1}\mathcal{D}[U_{\mathrm{fb}1} a_1]\rho + \kappa_{a_2}\mathcal{D}[U_{\mathrm{fb}2} a_2]\rho \\ & + \sum_{i=1,2}\sum_{j=A,B}\gamma_i^j \mathcal{D}[\sigma_i^j]\rho, \end{aligned} \tag{1}$$

where $a_{1(2)}$ and $a_{1(2)}^\dagger$ are the annihilation and creation operators of the cavity mode $a_{1(2)}$ with the spontaneous photon leakage rate $\kappa_{a_{1(2)}}$, respectively. The γ_i^j is the rate of spontaneous emission from the excited state to the ground state of the jth atom. The effect of decoherence superoperator $\mathcal{D}$ is $\mathcal{D}[c]\rho \equiv c\rho c^\dagger - (c^\dagger c\rho + \rho c^\dagger c)/2$. The collective amplitude damping operators are $J_{1(2)}^- = \sigma_{1(2)}^A + \sigma_{1(2)}^B$ and $J_i^+ = [J_i^-]^\dagger$ with $\sigma_1^A = |0\rangle_A\langle 1|$, $\sigma_2^A = |0\rangle_A\langle 2|$, $\sigma_1^B = |1\rangle_B\langle 0|$, and $\sigma_2^B = |2\rangle_B\langle 0|$. The cavity modes are not interesting as their behavior is slaved to driving for the high levels of damping. Let us now try to come back to the system of two atoms. Since the amplitudes of cavity modes are small, the density matrix ρ only needs to be partially expanded in terms of the small photon number states of cavity modes a_1 and a_2. In the limit where the cavity decay rates are very large, i.e., $\kappa_{a_{1(2)}} \gg g_{1(2)}$, the cavity modes can be adiabatically eliminated by neglecting the terms greater than second order.[38–40] Then, we can obtain the following master equation only prompting the atomic evolution:

$$\begin{aligned}\dot{\rho} =& -\mathrm{i}\Omega_1[(J_1^+ + J_1^-),\rho] - \mathrm{i}\Omega_2[(J_2^+ + J_2^-),\rho] \\ & + \Gamma_1\mathcal{D}[U_{\mathrm{fb}1} J_1^-]\rho + \Gamma_2\mathcal{D}[U_{\mathrm{fb}2} J_2^-]\rho \\ & + \sum_{i=1,2}\sum_{j=A,B}\gamma_i^j \mathcal{D}[\sigma_i^j]\rho, \end{aligned} \tag{2}$$

where $\Gamma_{1(2)} = 4g_{1(2)}^2/\kappa_{a_{1(2)}}$ describes the effective collective damping strength of the two atoms and the cavity mode $a_{1(2)}$. Furthermore, we assume that the collective decay rate Γ_i is much larger than the atomic spontaneous emission rate γ_i^j. Here, the effect of the spontaneous emission is temporarily ignored. The final effective master equation of the system can be written as

$$\begin{aligned}\dot{\rho} =& -\mathrm{i}\Omega_1[(J_1^+ + J_1^-),\rho] - \mathrm{i}\Omega_2[(J_2^+ + J_2^-),\rho] \\ & + \Gamma_1\mathcal{D}[U_{\mathrm{fb}1} J_1^-]\rho + \Gamma_2\mathcal{D}[U_{\mathrm{fb}2} J_2^-]\rho. \end{aligned} \tag{3}$$

This master equation describes the evolution of an open two-atom system with two collective decay channels, simultaneously driven by two classical fields. Before a feedback control is introduced, equation (3) does not have a unique steady solution.[39,41] Nonetheless, the steady-state solutions of Eq. (3) include the desired target state

$$|\psi_3\rangle = \frac{1}{\sqrt{3}}(|00\rangle - |11\rangle - |22\rangle), \tag{4}$$

which is a three-dimensional maximally entangled state.[15,19,21] We need to choose an effective feedback control to make the three-dimensional entangled state a unique steady state. The feedback operators can involve one atom or both atoms of the system, as long as the feedback controls break the symmetry with respect to the exchange of atoms. We choose the relatively simple and easily scalable feedback operators $U_{\mathrm{fb}1} = \exp[-\mathrm{i}\lambda_1(\sigma_1^B + \sigma_1^{B\dagger})]$ and $U_{\mathrm{fb}2} = \exp[-\mathrm{i}\lambda_2(\sigma_2^B + \sigma_2^{B\dagger})]$ with the control strength $\lambda_{1(2)}$, which are two local feedback controls. By solving Eq. (3) numerically, it can be proved that the three-dimensional entangled state $|\psi_3\rangle$ is the unique steady-state solution for the above local feedback controls.

3. Results and error analysis

As is well known, fidelity is a good assessment of the attainable precision of the state preparation scheme, so the definition of state fidelity $F = \sqrt{\langle\psi|\rho|\psi\rangle}$[42] is adopted to estimate our feedback scheme. On the basis of the effective master equations (2) and (3), the target state fidelity for different feedback and driving strengths is shown in Fig. 2 when atoms A and B are initially in the ground state $|01\rangle_{AB}$. For the sake of simplicity, we set $\Gamma_1 = \Gamma_2 = \Gamma, \Omega_1 = \Omega_2 = \Omega$,

$\lambda_1 = \lambda_2 = \lambda$, and $\gamma_i^j = \gamma$. It is seen that the target state fidelity is not significantly affected by the fluctuations of the feedback and driving strengths. From Fig. 2(a), we can evidently observe that a steady three-dimensional entangled state $|\psi_3\rangle$ with $F = 1$ can be generated for a wide range of parameters where the effect of the atomic spontaneous emission is not taken into account. Even if there is atomic spontaneous emission $\gamma = 0.01\Gamma$, the maximum value of the fidelity can still reach 0.96, as shown in Fig. 2(b). In comparison to Fig. 2(a), the fidelity of the steady state slightly reduces with atomic spontaneous emissions. In fact, our scheme does not require the identical feedback strengths for two collective decay channels in the feedback procedure. The fidelity for different feedback strengths corresponding to two decay channels is plotted in Fig. 3 based on Eqs. (2) and (3). Figure 3 shows that the feedback strength range corresponding to the target state with high fidelities is very wide. In the absence of spontaneous emission, even $\lambda_{2(1)} = 0$, the perfect target state is also achievable. That is to say, the three-dimensional entangled state can still be obtained via feedback control for one of decay channels. If the spontaneous emission $\gamma = 0.01\Gamma$, the fidelity of the target state is higher than 0.9 for many different values of λ_1 and λ_2. Thus, the scheme is robust against the imperfections in the feedback Hamiltonian.

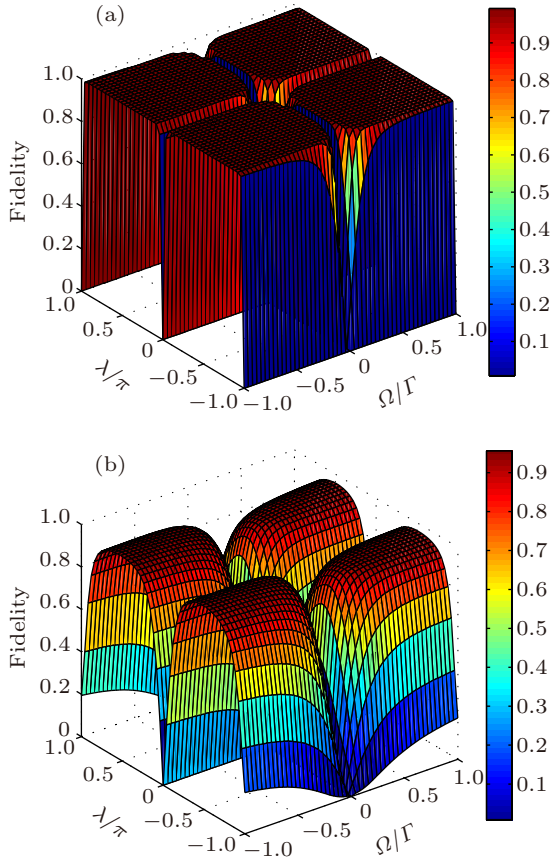


Fig. 2. (color online) Target state fidelity as a function of feedback and driving strengths for the local feedback control (a) without atomic spontaneous emission and (b) with $\gamma = 0.01\Gamma$.

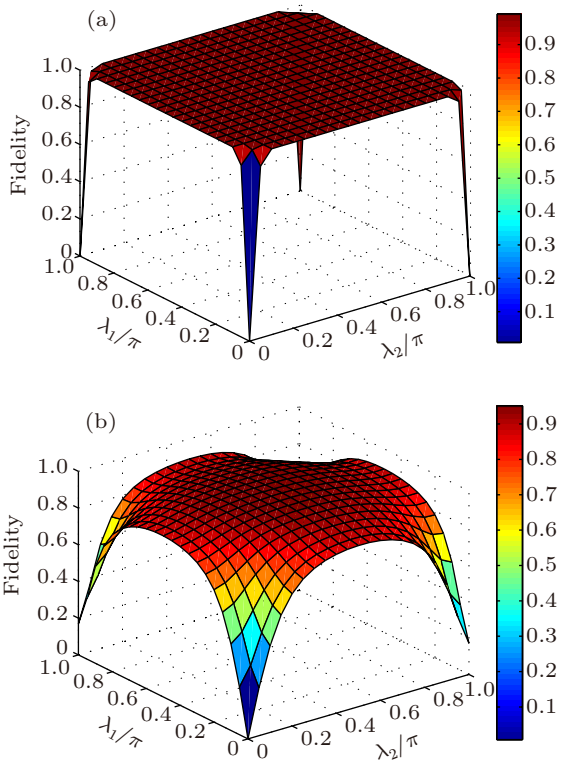


Fig. 3. (color online) Fidelity of the steady target state for different feedback strengths corresponding to two decay channels (a) without atomic spontaneous emission and (b) with $\gamma = 0.01\Gamma$. $\Gamma_1 = \Gamma_2 = \Gamma$, $\Omega_1 = \Omega_2 = \Gamma$.

Aside from the errors in the feedback strengths, the atom–cavity coupling constant and classical field driving strength asymmetry for two atoms may affect the target steady-state generation in the experimental operation. In cavity quantum electrodynamics systems, longitudinal confinement prevents fluctuation of the atomic positions along the cavity axis.[43] Nevertheless, it is possible that there is a static difference in the couplings of the two atoms. Thus, it is necessary to discuss the errors in coupling strengths corresponding to both atoms in the cavity. At the same time, the classical field driving strength difference is also taken into account. Suppose there are some deviations, i.e., $g^B_{1(2)} = (1+\delta_{1(2)})g_{1(2)}$ and $\Omega^B_{1(2)} = (1+\delta_{3(4)})\Omega_{1(2)}$ with $g^A_{1(2)} = g_{1(2)}$ and $\Omega^A_{1(2)} = \Omega_{1(2)}$. The corresponding effective master equation becomes

$$\begin{aligned}\dot{\rho} = & -\mathrm{i}\left[\Omega_1^A(\sigma_1^A + \sigma_1^{A\dagger}) + \Omega_1^B(\sigma_1^B + \sigma_1^{B\dagger}), \rho\right] \\ & -\mathrm{i}\left[\Omega_2^A(\sigma_2^A + \sigma_2^{A\dagger}) + \Omega_2^B(\sigma_2^B + \sigma_2^{B\dagger}), \rho\right] \\ & + \frac{4}{\kappa_{a_1}}\mathcal{D}\left[U_{\mathrm{fb1}}(g_1^A\sigma_1^A + g_1^B\sigma_1^B)\right]\rho \\ & + \frac{4}{\kappa_{a_2}}\mathcal{D}\left[U_{\mathrm{fb2}}(g_2^A\sigma_2^A + g_2^B\sigma_2^B)\right]\rho. \end{aligned} \tag{5}$$

It is undoubted that the target state fidelity would decrease due to the existence of δ_k $(k = 1,2,3,4)$. However, a high fidelity can still be obtained in a certain range of errors, as shown in Fig. 4. Surprisingly, the target state fidelity is greater than 0.99 under the condition $\delta_1, \delta_2 \in [-0.1, 0.1]$, and $\delta_3 = \delta_4 = 0$, while the fidelity is above 0.97 when $\delta_3, \delta_4 \in [-0.05, 0.05]$ and $\delta_1 = \delta_2 = 0$.

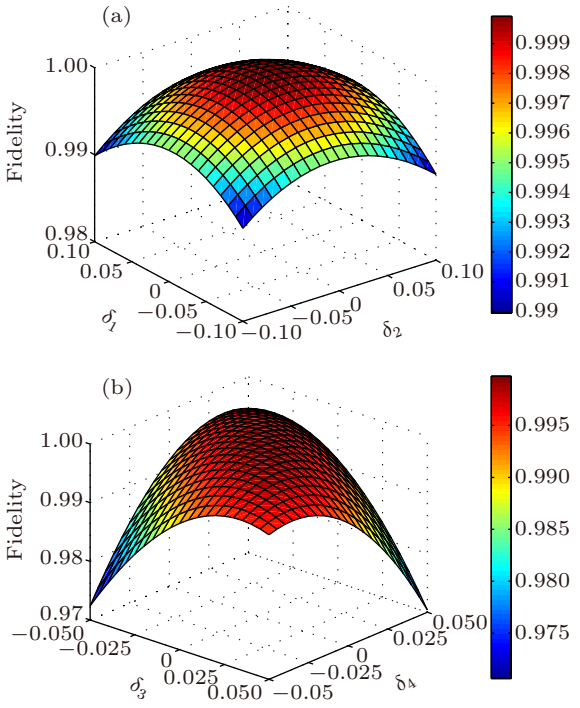


Fig. 4. (color online) Fidelity of the three-dimensional entangled state versus (a) atom–cavity coupling error and (b) driving strength error, respectively, with $\Gamma_1 = \Gamma_2 = \Gamma$, $\Omega_1 = \Omega_2 = \Gamma$, and $\lambda_1 = \lambda_2 = \pi/2$.

Up to now, all of the results are obtained based on the perfect detection. Because the feedback control for the system relies on the measurement results, evaluating the influence of detection inefficiencies is very important. To take this factor into account, the corresponding master equation (3) should be modified as

$$\begin{aligned}\dot{\rho} = & -\mathrm{i}\Omega_1[(J_1^+ + J_1^-),\rho] - \mathrm{i}\Omega_2[(J_2^+ + J_2^-),\rho] \\ & + \eta_1\Gamma_1\mathcal{D}[U_{\mathrm{fb}1}J_1^-]\rho + \eta_2\Gamma_2\mathcal{D}[U_{\mathrm{fb}2}J_2^-]\rho \\ & + (1-\eta_1)\Gamma_1\mathcal{D}[J_1^-]\rho + (1-\eta_2)\Gamma_2\mathcal{D}[J_2^-]\rho \\ & + \sum_{i=1,2}\sum_{j=A,B}\gamma_i^j\mathcal{D}[\sigma_i^j]\rho, \end{aligned} \tag{6}$$

where $\eta_{1(2)}$ represents the detector efficiency. Equation (6) shows two situations: (i) the term with the factor $\eta_{1(2)}$ describes that we can obtain information from the detector and implement the feedback transformation $U_{\mathrm{fb}1(2)}$; (ii) the term with the factor $(1-\eta_{1(2)})$ denotes that the information flows to the environment and there is no feedback control. Figure 5 illustrates that the effect of detection efficiencies on the fidelity of the three-dimensional entangled state when both atoms are initially in the ground state $|01\rangle_{AB}$. The steady state of the system is always the target state $|\psi_3\rangle$ in the absence of spontaneous atomic emission. The imperfect detection only delays the time at which the steady state is achieved in comparison to the perfect case. In the presence of spontaneous emission, the target state fidelity decreases as detection efficiency decreases. This is reasonable as less efficient detection will weaken the effective control. The balance between decay and feedback dynamics is broken. Nonetheless, in the case of $\gamma = 0.01\Gamma$, the decline of the fidelity is small and it is still higher than 0.9 even if $\eta = 0.5$.

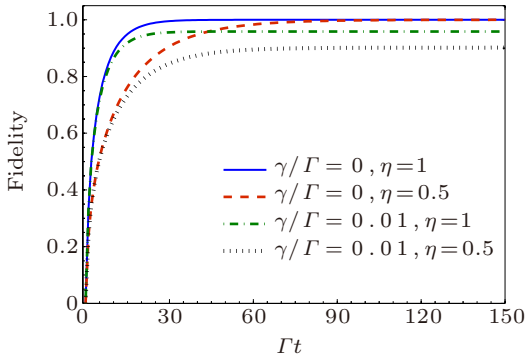


Fig. 5. (color online) Effect of different detection efficiencies on the fidelity of the three-dimensional entangled state with and without spontaneous atomic emission for $\eta_{1(2)} = \eta$, $\Omega_{1(2)} = \Gamma$, and $\lambda_{1(2)} = \pi/2$.

In addition, the correctness of the adiabatic approximation for the cavity modes can be checked by the master equation (1) without any approximation. In the adiabatic regime, the fidelity of the target state is about 0.95 by solving Eq. (1) with the corresponding parameters $\kappa_{a_1(a_2)} = 1600\gamma$, $g_{1(2)} = 200\gamma$, $\Omega_{1(2)} = 100\gamma$, and $\lambda_{1(2)} = \pi/2$. This result is close to that from the effective model, and thus shows the reliability of the adiabatic approximation.

Let us briefly analyze the experimental implementation of the scheme. The atomic V-type and Λ-type level configurations involved in our scheme can both be implemented with ^{87}Rb hyperfine levels, whose relevant atomic levels are shown in Fig. 6. The states $|0\rangle_{A(B)}$, $|1\rangle_{A(B)}$, and $|2\rangle_{A(B)}$ correspond to $|F=1, m_F=0\rangle$ of $5^2\mathrm{S}_{1/2}$ ($5^2\mathrm{P}_{1/2}$), $|F=1, m_F=-1\rangle$ of $5^2\mathrm{P}_{1/2}$ ($5^2\mathrm{S}_{1/2}$), and $|F=1, m_F=1\rangle$ of $5^2\mathrm{P}_{1/2}$ ($5^2\mathrm{S}_{1/2}$), respectively. Each atom couples resonantly to two classical fields $\Omega_{1,2}$ and two circularly polarized photon modes $a_{1,2}$ of the cavity corresponding to left and right circular polarizations, respectively. In recent experiments, for an optical cavity approaching the bad-cavity limit, where the atom-cavity cooperativity parameter is $C = g^2/\kappa\gamma \approx 19$[44] with $(\kappa, g, \gamma) \sim 2\pi \times (255.05, 70, 1)$ MHz,[45] the fidelity of the target state is about 90% based on Eq. (1) in the case of $\Omega_{1(2)} = g/2$ and $\lambda_{1(2)} = \pi/2$. The value is relatively high for the generation of stable entangled states. A better bad-cavity regime is expected in future cavity quantum electrodynamics experiments.

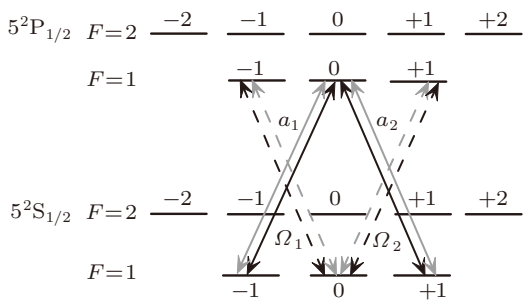


Fig. 6. V-type and Λ-type level schemes of the atoms by means of ^{87}Rb hyperfine levels.

4. Generalization of the model

It is worth noting that the current scheme can be extended to prepare N-dimensional entangled states of two particles. The potential level configurations for atoms A and B are shown in Fig. 7. Suppose that there is a multimode optical cavity with $(N-1)$ discrete modes. The master equation describing this system can be written as

$$\dot{\rho} = \sum_{i=1}^{N-1} -\mathrm{i}\Omega_i[(J_i^+ + J_i^-),\rho] - \mathrm{i}g_i[(J_i^+ a_i + J_i^- a_i^\dagger),\rho] + \kappa_{a_i}\mathcal{D}[U_{\mathrm{fb}i}a_i]\rho + \sum_{j=A,B}\gamma_i^j\mathcal{D}[\sigma_i^j]\rho, \quad (7)$$

where a_i $(i = 1,2,\ldots,N-1)$ is the annihilation operator of the ith cavity mode with the coupling constant g_i and decay rate κ_{a_i}. In the scheme, we need $(N-1)$ lasers for the case of N-dimensional entanglement. Ω_i denotes the Rabi frequency of the ith classical field. The specific transitions between the atomic levels are shown in Fig. 7. The collective amplitude damping operators are $J_i^- = \sigma_i^A + \sigma_i^B$ with $\sigma_i^A = |0\rangle_A\langle i|$ and $\sigma_i^B = |i\rangle_B\langle 0|$.

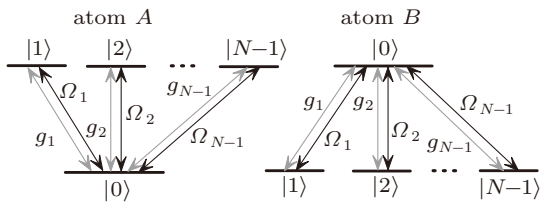


Fig. 7. Potential level configurations of atoms A and B for N-dimensional entangled states.

Similar to the adiabatical approximation process in Section 2, by neglecting the highly excited modes in the limit $\kappa_{a_i} \gg g_i \gg \gamma_i^j$, the effective master equation can be obtained as

$$\dot{\rho} = \sum_{i=1}^{N-1} -\mathrm{i}\Omega_i[(J_i^+ + J_i^-),\rho] + \Gamma_i\mathcal{D}[U_{\mathrm{fb}i}J_i^-]\rho, \quad (8)$$

with the effective collective decay rate $\Gamma_i = 4{g_i}^2/\kappa_{a_i}$. Here the feedback operation still only acts on atom B. When the corresponding feedback operator is chosen as $U_{\mathrm{fb}i} = \exp[-\mathrm{i}\lambda_i(\sigma_i^B + \sigma_i^{B\dagger})]$, we can obtain a perfect N-dimensional entangled state

$$|\psi_N\rangle = \frac{1}{\sqrt{N}}(|00\rangle - |11\rangle - |22\rangle - \cdots - |N-1,N-1\rangle). \quad (9)$$

Take a four-dimensional entangled state for example, the target state with the fidelity $F = 1$ can be achieved without spontaneous atomic emission, while the fidelity of the target sate still arrives at 93.7% with the spontaneous atomic emission $\gamma_i^j \equiv \gamma = 0.01\Gamma$, where we have set other common parameters as $\Gamma_i = \Gamma$, $\Omega_i = 3\Gamma$, and $\lambda_i = \pi/2$ for simplicity.

5. Conclusion

In this paper, we have put forward a scheme to dissipatively prepare steady high-dimensional entangled states by using local feedback control based on quantum-jump detection. This engineered evolution dynamically controls the system towards the unique target steady state, so the scheme needs neither the atomic state initialization nor strict control of the interaction time. The possible factors affecting the scheme are discussed in detail. The scheme performs well even in the presence of detection inefficiencies and parameter imperfections. This feedback procedure can reduce the impact of spontaneous emissions. More interestingly, the present scheme can be generalized to the case of N-dimensional bipartite entangled states in theory.

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