Vol 17 No 3, March 2008
1674-1056/2008/17(03)/0789-05
Chinese Physics B
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# Generation of nonclassical states in a large detuning cavity*

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(Received 12 June 2007; revised manuscript received 10 October 2007)

By using the theory of cavity QED, we study the system in which a two-level atom interacts with a cavity in the case of large detuning. Through the selective detecting of atomic state, Schrödinger cat states and entangled coherent states are easily generated. When the atom is driven by a weak classical field and the cavity field is in the Schrödinger cat state, we study the conditions of generating the Fock states and the maximal success probability. The maximal success probability in our scheme is larger than the previous one.

**Keywords:** quantum optics, the Fock state, Schrödinger cat state, entangled coherent state
**PACC:** 0365, 4250

## 1. Introduction

The generation of various nonclassical states of an electromagnetic field is an important topic in quantum optics.[1] The particular interest is how to generate the Fock states, because these states exhibit fluctuations in intensity. According to the theory of cavity QED, many schemes have been proposed to generate Fock states by using resonant interactions between two-level atoms.[2−4] In order to generate the $N$-photon state one should use $N$ atoms. One- and two-photon states of a cavity field have been generated in this way.[5] On the other hand, other schemes have also been proposed for generating the Fock states by using a single atom,[6−12] but none of them has been implemented in the cavity QED. Recently, the production of a two-photon state has been reported by using a single atom in a high-$Q$ cavity.[13] In Ref.[14] Zheng proposed a scheme in which a two-level atom was sent through the cavity and driven by a weak classical field. The atom interacted with the coherent state field in the condition of the larger detuning, and Zheng pointed out that the success probability of generating a three-photon Fock state was 0.166.

Recently, more and more people have been interested in Schrödinger cat states. So far, many schemes have been presented to generate such states. Yurke and Stoler[15] have shown that under certain conditions, a coherent state propagating through an amplitude dispersive medium can evolve into a superposition of two coherent states with a phase difference of $\pi$. Gerry[16] has proposed a technique for generating the superposition of four coherent states symmetrically located on a circle in phase space according to the theory of dispersive cavity QED. Brune and Haroche[17] have proposed a method to convert an initial coherent state of a field into a superposition of four coherent states based on the detection of the dispersive phase shift produced by the field on the wave function of non-resonant atoms crossing the cavity. Guo and Zheng[18] have presented a scheme for generating Schrödinger cat states with controllable weighting factors based on state-selective measurements on atoms passing through a non-resonant cavity, and so on. In this paper, we also present a method to generate cavity field Schrödinger cat state via cavity QED in the case of large detuning. Here we can see that the cavity field Schrödinger cat state is generated more easily now than before. Much attention has been paid to the entangled coherent states in the study of quantum entanglement.[19−21] Many methods have been studied to generate the entangled coherent state. In our scheme we can generate the entangled coherent state easily through Bell-state measurement.

According to Ref.[14], choosing the cavity field which is in the Schrödinger cat state, we can acquire

*Project supported by the National Science Foundation of China (Grant No 10774088), the Key Program of National Science Foundation of China (Grant No 10534030) and the Funds from Qufu Normal University, China (Grant No XJ0621).
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our desired Fock state much more easily than before. The maximal success probability of generating the desired Fock state in our paper is larger than in Ref.[14]. That is to say, our scheme is more feasible.

## 2. Theoretical model and generation of Schrödinger cat states

We consider a two-level atom interacting with a single-mode cavity and driven by a classical field. The Hamiltonian is

$$\begin{aligned} H =&\omega_0 S_z + \omega_a a^+ a + g(a^+ S^- + aS^+) \\ &+ \varepsilon(S^+ \mathrm{e}^{-\mathrm{i}\omega t} + S^- \mathrm{e}^{\mathrm{i}\omega t}), \end{aligned} \tag{1}$$

where $a^+$ and $a$ are the creation and annihilation operators for the cavity field, respectively; $S_z = |e\rangle\langle e| - |g\rangle\langle g|$, $S^+ = |e\rangle\langle g|$ and $S^- = |g\rangle\langle e|$ are the inversion, raising, and lowering operators for the atom, respectively with $|e\rangle$ and $|g\rangle$ being the excited state and the ground state of the two-level atom; $\omega_0$, $\omega_a$ and $\omega$ are the frequencies respectively for the atomic transition, cavity mode, and classical field; $g$ is the coupling constant between the atom and the cavity field; $\varepsilon$ is the coupling constant between the atom and the classical field. In the interaction picture the Hamiltonian for the system is given by

$$H_{\mathrm{I}} = H_{\mathrm{I},1} + H_{\mathrm{I},2}, \tag{2}$$

where

$$H_{\mathrm{I},1} = g(a^+ S^- \mathrm{e}^{-\mathrm{i}\delta t} + aS^+ \mathrm{e}^{\mathrm{i}\delta t}), \tag{3}$$

$$H_{\mathrm{I},2} = \varepsilon(S^+ \mathrm{e}^{\mathrm{i}\Delta t} + S^- \mathrm{e}^{-\mathrm{i}\Delta t}) \tag{4}$$

with $\delta = \omega_0 - \omega_a$ and $\Delta = \omega_0 - \omega$. Suppose that the detuning $\delta$ is much larger than the coupling strength, and there will be no energy exchange between the atom and the cavity mode. Then the atom–cavity interaction is dispersive and thus the Hamiltonian $H_{\mathrm{I},1}$ can be rewritten as[22]

$$H_{\mathrm{I},1} = \frac{g^2}{\delta}(aa^+|e\rangle\langle e| - a^+ a|g\rangle\langle g|). \tag{5}$$

Equation (5) holds when $\delta \gg g\sqrt{M}$. $M$ is the mean photon number of the cavity field.

The time evolution of this system is determined by Schrödinger's equation

$$\mathrm{i}\frac{\mathrm{d}|\Psi(t)\rangle}{\mathrm{d}t} = H_{\mathrm{I}}|\Psi(t)\rangle. \tag{6}$$

Perform the unitary transformation

$$|\Psi(t)\rangle = \mathrm{e}^{-\mathrm{i}H_{I,1}t}|\Psi'(t)\rangle, \tag{7}$$

then we will obtain

$$\mathrm{i}\frac{\mathrm{d}|\Psi'(t)\rangle}{\mathrm{d}t} = H'_{I,2}|\Psi'(t)\rangle, \tag{8}$$

where

$$\begin{aligned} H'_{\mathrm{I},2} =&\varepsilon(S^+ \mathrm{e}^{\mathrm{i}[\Delta + \frac{g^2}{\delta}(aa^+ + a^+ a)]t} \\ &+ S^- \mathrm{e}^{-\mathrm{i}[\Delta + \frac{g^2}{\delta}(aa^+ + a^+ a)]t}). \end{aligned} \tag{9}$$

In this system, the Schrödinger cat state is easy to generate. Assume that there is no coupling between the atom and the classical field, then the theoretical model will be that a two-level atom interacts with a single cavity in the case of the large detuning. The effective Hamiltonian for the system can be given by expression (5), then the unitary evolution operator becomes

$$U = \mathrm{e}^{-\mathrm{i}H_{\mathrm{I},1}t}. \tag{10}$$

We consider that the cavity is initially in a coherent state $|\mu\rangle = \sum_n f_n|n\rangle$ and the atom is initially in the state of $\frac{1}{\sqrt{2}}(|g\rangle + |e\rangle)$. The time evolution of the system state can be obtained to be

$$\begin{aligned} |\Psi(t)\rangle =&U\sum_n [f_n|n\rangle \otimes \frac{1}{\sqrt{2}}(|g\rangle + |e\rangle)] \\ =&\mathrm{e}^{-\mathrm{i}\frac{g^2}{\delta}(aa^+|e\rangle\langle e| - a^+ a|g\rangle\langle g|)} \sum_n [f_n|n\rangle \otimes \frac{1}{\sqrt{2}}(|g\rangle + |e\rangle)] \\ =&\frac{1}{\sqrt{2}}\sum_n f_n[\mathrm{e}^{-\mathrm{i}\frac{g^2}{\delta}t}\mathrm{e}^{-\mathrm{i}\frac{g^2}{\delta}nt}|n, e\rangle + \mathrm{e}^{\mathrm{i}\frac{g^2}{\delta}nt}|n, g\rangle] \\ =&\frac{1}{\sqrt{2}}(\mathrm{e}^{-\mathrm{i}\frac{g^2}{\delta}t}|\mu\mathrm{e}^{-\mathrm{i}\frac{g^2}{\delta}t}\rangle|e\rangle + |\mu\mathrm{e}^{\mathrm{i}\frac{g^2}{\delta}t}\rangle|g\rangle). \end{aligned} \tag{11}$$

The two-level atom is measured at time $t'$ in the $\frac{1}{\sqrt{2}}(|e\rangle \pm |g\rangle)$ basis, leaving the field in the state

$$|\Psi_{\rm f}\rangle = \frac{1}{2}(e^{-i\frac{g^2}{\delta}t'}|\mu e^{-i\frac{g^2}{\delta}t'}\rangle \pm |\mu e^{i\frac{g^2}{\delta}t'}\rangle). \quad (12)$$

Equation (12) shows that the measurement of the atomic state will produce the superposition of the coherent states $N(|\alpha\rangle \pm e^{i\phi}|\beta\rangle)$, where $\alpha = \mu e^{i\frac{g^2}{\delta}t'}$, $\beta = \mu e^{-i\frac{g^2}{\delta}t'}$, $\phi = -\frac{g^2}{\delta}t'$, and $\frac{g^2t'}{\delta} \neq 2n\pi$, $(n = 0, 1, 2, \cdots)$.

## 3. Generation of Fock state

We consider that a two-level atom is sent through the cavity and driven by a weak classical field. Assume that the cavity is initially in Schrödinger cat state $N(|\alpha\rangle + e^{i\phi}|\beta\rangle)$, where $N = \frac{1}{\sqrt{2+2\cos\phi e^{-|\alpha-\beta|}}}$, and the atom is initially in the state $|g\rangle$, then the state of the coupling system $(t = 0)$ will be

$$|\Psi'(0)\rangle = N(|\alpha\rangle + e^{i\phi}|\beta\rangle) \otimes |g\rangle, \quad (13)$$

where $|\alpha\rangle = \sum_{n=0}^{\infty} C_n|n\rangle$, $|\beta\rangle = \sum_{n=0}^{\infty} \rho_n|n\rangle$ and $C_n = e^{-\frac{|\alpha|^2}{2}}\frac{\alpha^n}{\sqrt{n!}}$, with $\rho_n = e^{-\frac{|\beta|^2}{2}}\frac{\beta^n}{\sqrt{n!}}$. In the case of $n > |\alpha|^2$, and $n > |\beta|^2$, both $|C_n|^2$ and $|\rho_n|^2$ decrease fast as $n$ increases. Therefore, there exists such an integer $M$ that $\sum_{n=m+1}^{\infty}|C_n|^2 \ll 1$ and $\sum_{n=m+1}^{\infty}|\rho_n|^2 \ll 1$ hold true. In the case, the coherent state approximates the superposition of the first $M+1$ Fock states, i.e.

$$|\alpha\rangle \simeq \sum_{n=0}^{M} C_n|n\rangle, \quad |\beta\rangle \simeq \sum_{n=0}^{M}\rho_n|n\rangle. \quad (14)$$

After an interaction time $(t > 0)$, the state of the whole system is

$$|\Psi'(t)\rangle = \sum_n [C_1|n, g\rangle + C_2|n, e\rangle]. \quad (15)$$

Substituting expressions (9) and (15) into Eq.(8), we can obtain

$$i\dot{C}_1 = \varepsilon C_2 e^{-i\Delta_n t}, \quad i\dot{C}_2 = \varepsilon C_1 e^{i\Delta_n t}, \quad (16)$$

where $\Delta_n = (2n+1)\frac{g^2}{\delta} + \Delta$. Considering the initially condition (13), from Eq.(16) it follows that

$$\begin{aligned} C_1 =& N(C_n + e^{i\phi}\rho_n)e^{-i\frac{\Delta_n t}{2}}\left(\cos\left(\sqrt{\varepsilon^2+\frac{\Delta_n^2}{4}}t\right) + \frac{i\Delta_n}{\sqrt{4\varepsilon^2+\Delta_n^2}}\sin\left(\sqrt{\varepsilon^2+\frac{\Delta_n^2}{4}}t\right)\right), \\ C_2 =& -iN(C_n + e^{i\phi}\rho_n)e^{i\frac{\Delta_n t}{2}}\frac{2\varepsilon}{\sqrt{4\varepsilon^2+\Delta_n^2}}\sin\left(\sqrt{\varepsilon^2+\frac{\Delta_n^2}{4}}t\right). \end{aligned} \quad (17)$$

After an interaction time $t$ the state of the whole system is

$$\begin{aligned} |\Psi'(t)\rangle \simeq N\sum_{n=0}^{M}(C_n + e^{i\phi}\rho_n)\Bigg[&e^{-i\frac{\Delta_n t}{2}}\left(\cos\left(\sqrt{\varepsilon^2+\frac{\Delta_n^2}{4}}t\right) + \frac{i\Delta_n}{\sqrt{4\varepsilon^2+\Delta_n^2}}\sin\left(\sqrt{\varepsilon^2+\frac{\Delta_n^2}{4}}t\right)\right)|n, g\rangle \\ &- ie^{i\frac{\Delta_n t}{2}}\frac{2\varepsilon}{\sqrt{4\varepsilon^2+\Delta_n^2}}\sin\left(\sqrt{\varepsilon^2+\frac{\Delta_n^2}{4}}t\right)|n, e\rangle\Bigg]. \end{aligned} \quad (18)$$

If we now detect the atom in the state $|e\rangle$, the cavity field collapses into

$$\begin{aligned} |\Psi_{\rm c}(t)\rangle \simeq N_{\rm c}\sum_{n=0}^{M} Ne^{i\frac{\Delta_n t}{2}}(C_n + e^{i\phi}\rho_n)\frac{2\varepsilon}{\sqrt{4\varepsilon^2+\Delta_n^2}} \\ \times \sin\left(\sqrt{\varepsilon^2+\frac{\Delta_n^2}{4}}t\right)|n\rangle, \end{aligned} \quad (19)$$

and $N_{\rm c}$ is a normalization factor. Choose the frequency of the classical field appropriately such that $\Delta_{n_0} = 0$. In this case, for the Fock state $|n_0\rangle$ the atom is tuned to being in resonance with the classical field, while for $|n\rangle$ $(n \neq n_0)$ $\Delta_n = \frac{2(n-n_0)g^2}{\delta}$. Then we have

$$\begin{aligned} |\Psi_{\rm c}(t)\rangle \simeq N_{\rm c}N[&(C_{n_0} + e^{i\phi}\rho_{n_0})\sin(\varepsilon t)|n_0\rangle \\ &+ \sum_{n\neq n_0}(C_n + e^{i\phi}\rho_n)p_n|n\rangle], \end{aligned} \quad (20)$$

where

$$p_n = e^{\frac{i\Delta_n t}{2}}\frac{2\varepsilon}{\sqrt{4\varepsilon^2+\Delta_n^2}}\sin\left(\sqrt{\varepsilon^2+\frac{\Delta_n^2}{4}}t\right). \quad (21)$$

In the case $g^2/\delta \gg \varepsilon$ and $|\sin\left(\sqrt{\varepsilon^2+\frac{\Delta_n^2}{4}}t\right)| \ll 1$,

$p_n \ll 1$ ($n \neq n_0$). Thus, for Fock states $|n\rangle$ ($n \neq n_0$) the atom has a negligible probability of undergoing a transition. Therefore, the final field state approximates the Fock state $|\Psi_c(t)\rangle \simeq N_c N(C_{n_0} + e^{i\phi}\rho_{n_0})\sin(\varepsilon t)|n_0\rangle$. The success probability of the scheme is $N^2|(C_{n_0} + e^{i\phi}\rho_{n_0})\sin(\varepsilon t)|^2$. In Ref.[14] Zheng proposed that a two-level atom was sent through a coherent cavity and driven by a weak classical field, and the success probability of Zheng's scheme was $|C_{n_0}\sin(\varepsilon t)|^2$. For simplicity, take $\beta = \alpha e^{i\theta}$, then we will have

$$\begin{aligned}\gamma =& \frac{N^2|(C_{n_0} + e^{i\phi}\rho_{n_0})\sin(\varepsilon t)|^2}{|C_{n_0}\sin(\varepsilon t)|^2} \\ =& N^2|1 + e^{i(\phi+\theta n_0)}|^2 \\ =& \frac{|1 + e^{i(\phi+\theta n_0)}|^2}{2 + 2\cos\phi e^{-(2-2\cos\theta)|\alpha|^2}}. \end{aligned} \tag{22}$$

Equation (22) shows that we can choose $\theta$ and $\phi$ appropriately, the maximal success probability of our scheme is larger than that in Ref.[14]. For example, set $\phi = \pi$, $\theta = \pi$, and $n_0$ to be an odd number, then $\gamma = \dfrac{4}{2 - 2e^{-4|\alpha|^2}} > 2$; set $\phi = 0$, $\theta = \pi$, and $n_0$ to be an even number, then $\gamma = \dfrac{4}{2 + 2e^{-4|\alpha|^2}} \approx 2$. So we can improve the maximal success probability of generating the Fock state.

Assume that the cavity field is initially in the so-called even or odd coherent state $\tilde{N}(|\alpha\rangle + e^{i\phi}|-\alpha\rangle)$, where $\tilde{N} = \dfrac{1}{\sqrt{2 + 2\cos\phi e^{-4|\alpha|^2}}}$, then $\phi = 0$ and $\phi = \pi$ will respond to the even coherent state and the odd coherent state,[23] respectively. The atom interacts dispersively with the cavity field and the weak classical field. If we detect the atom in the state $|e\rangle$, at time $t$ the cavity field will collapse into

$$\begin{aligned}|\Psi_s(t)\rangle \simeq N_s \sum_{n=0}^{M} \tilde{N} e^{i\frac{\Delta_n t}{2}}(C_n + e^{i\phi}C_n^-)\frac{2\varepsilon}{\sqrt{4\varepsilon^2 + \Delta_n^2}} \\ \times \sin\left(\sqrt{\varepsilon^2 + \frac{\Delta_n^2}{4}}t\right)|n\rangle. \end{aligned} \tag{23}$$

Also if $\Delta_{n_0} = 0$ and $p_n \ll 1$ are satisfied, $|\Psi_s(t)\rangle \simeq N_s\tilde{N}(C_{n_0} + e^{i\phi}C_{n_0}^-)\sin(\varepsilon t)|n_0\rangle$. The success probability of generating the desired Fock state is

$$\begin{aligned}&\tilde{N}^2|(C_{n_0} + e^{i\phi}C_{n_0}^-)\sin(\varepsilon t)|^2 \\ =& \tilde{N}^2|[1 + e^{i\phi}(-1)^{n_0}]C_{n_0}\sin(\varepsilon t)|^2. \end{aligned} \tag{24}$$

In the case where $\phi = 0$ and $n_0$ is an even number and in the case where $\phi = \pi$ and $n_0$ is an odd number, the maximal success probability of our scheme is larger than that in Ref.[14]. For example, we choose

$$|\alpha|^2 = n_0, \quad |C_{n_0}|^2 = e^{-n_0}\frac{n_0^{n_0}}{n_0!}, \tag{25}$$

and $n_0 = 1$, $g^2/\delta = 5\varepsilon$ and $g^2 t/\delta = \dfrac{5\pi}{2}$, then the maximal success probability of this scheme can reach 0.749. One-photon state is very useful for the quantum communication, here we can generate $|1\rangle$ easily. But in Ref.[14], the maximal probability of generating the one-photon state is only 0.368.

In Ref.[14], Zheng showed that the successful probability of generating the three-photon states was 0.166. We can set $n_0 = 3$, $g^2/\delta = 5\varepsilon$, and $g^2 t/\delta = \dfrac{5\pi}{2}$, then the maximal success probability of generating state $|3\rangle$ can reach 0.448. It is necessary to give a brief discussion on the experiment. For the Rydberg atoms with principle quantum numbers 49, 50, and 51, the radiative time $T_r$ is about $3 \times 10^{-2}$s, and the coupling constant $g$ is $2\pi \times 24$kHz.[13,24] With the choices of $\delta = 8g$ and $g = 40\varepsilon$, the required atom–cavity–field interaction time is $\pi/(2\varepsilon) \simeq 4.2 \times 10^{-4}$s for the generation of state $|3\rangle$. A cavity with a decay time $T_c \simeq 10^{-3}$s is achievable. Therefore, based on cavity QED techniques existing presently the proposed scheme might be realizable. We can see that the fidelity of generating the desired Fock state in our scheme is the same as that in Ref.[14].

## 4. Generation of entangled coherent state

We now turn to the problem of generating a two-mode entangled coherent state. Considering two two-level atoms dispersively interacting with two single-mode cavities, the two cavity modes have the same frequencies and coupling strengths with the atom. Suppose that $|\delta|$ is much larger than the coupling strength, then the effective Hamiltonian will be

$$H_{e,i} = \frac{g^2}{\delta}(a_i a_i^+|e_i\rangle\langle e_i| - a_i^+ a_i|g_i\rangle\langle g_i|). \tag{26}$$

Assume that the cavities are initially in coherent state $|\mu\rangle = \sum_n f_n|n\rangle$ and the atom is initially in the state $\dfrac{1}{\sqrt{2}}(|g_i\rangle + |e_i\rangle)$ $(i = 1, 2)$, then the initial state of one cavity will evolve into the following form:

$$\begin{aligned}|\Psi(t)\rangle_i &= e^{-iH_{e,i}t}|\mu\rangle \otimes \frac{1}{\sqrt{2}}(|g_i\rangle + |e_i\rangle) \\ &= \frac{1}{\sqrt{2}}(e^{-i\frac{g^2}{\delta}t}|\mu e^{-i\frac{g^2}{\delta}t}\rangle|e_i\rangle + |\mu e^{i\frac{g^2}{\delta}t}\rangle|g_i\rangle), \end{aligned} \tag{27}$$

where $\alpha = \mu e^{i\frac{g^2}{\delta}t}$, $\beta = \mu e^{-i\frac{g^2}{\delta}t}$, $\phi = -\dfrac{g^2}{\delta}t$, and $\dfrac{g^2 t}{\delta} \neq 2n\pi, (n = 0, 1, 2, \cdots)$. Then we can acquire the

state of the whole system as follows:

$$
\begin{aligned}
|\Phi\rangle =& \prod_{i=1}^{2} \frac{1}{\sqrt{2}}(\mathrm{e}^{\mathrm{i}\phi}|\alpha\rangle|e_i\rangle + |\beta\rangle|g_i\rangle) \\
=& \frac{N}{2\sqrt{2}}\Big[\frac{1}{\sqrt{2}}(|e,e\rangle + |g,g\rangle)\mathrm{e}^{\mathrm{i}\phi}(|\alpha,\alpha\rangle + \mathrm{e}^{-2\mathrm{i}\phi}|\beta,\beta\rangle) \\
& - \frac{1}{\sqrt{2}}(|e,e\rangle - |g,g\rangle)\mathrm{e}^{\mathrm{i}\phi}(|\alpha,\alpha\rangle - \mathrm{e}^{2\mathrm{i}\phi}|\beta,\beta\rangle) \\
& + \frac{1}{\sqrt{2}}(|g,e\rangle + |e,g\rangle)(|\alpha,\beta\rangle + |\beta,\alpha\rangle) \\
& - \frac{1}{\sqrt{2}}(|g,e\rangle - |e,g\rangle)(|\alpha,\beta\rangle - |\beta,\alpha\rangle)\Big], \qquad (28)
\end{aligned}
$$

where $N$ is the normalization constant. Expression (28) shows that we can acquire the four entangled coherent states by measuring the four Bell-states, respectively.

# 5. Conclusion

We have proposed a scheme for generating a Fock state via the driven Jaynes–Cummings model, in which a two-level atom interacts with both a classical field and a quantized cavity field. Firstly, we give a scheme to generate the superposition of two coherent states. Secondly, we choose the cavity to be a superposition state of two coherent states, so the maximal success probability of generating the desired Fock state in our paper is larger than that in Ref.[14]. That is to say, the scheme we have proposed is more feasible. Our scheme may open the way to the Fock state engineering. Finally, we propose a scheme for generating four entangled coherent states via Bell-state measurement.

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