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Generation of cluster-type entangled squeezed vacuum states*

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We present a scheme to prepare cluster-type entangled squeezed vacuum states (CTESVS) by considering the two-photon interaction between a two-level atom and a high-quality cavity, driven by a strong classical field. After the realization of simple atomic measurements, the generation of CTESVS in four separate cavities is accomplished within the cavity decay time. In the case of large atom–cavity detuning, the scheme is immune to the effect of atomic spontaneous emission.

Keywords: cluster state, squeezed vacuum state, quantum entanglement
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1. Introduction

Quantum entanglement is at the heart of quantum information and computing science.[1,2] Entanglement is not only widely used for quantum dense coding,[3] quantum cryptography[4,5] and quantum teleportation,[6,7] but also opens up possibilities for the testing of quantum nonlocality.[8,9] While bipartite entanglement is well understood, multipartite entanglement is still under extensive exploration. It has been shown that there are two different classes of tripartite entanglement states: the Greenberger–Horne–Zeilinger (GHZ) class[8] and the W class,[10] under stochastic local operation and classical communication. Recently, Briegel and Raussendorf introduced another class of N-qubit entangled states, i.e. the cluster states,[11] which have some interesting features. They have a high persistence of entanglement, that is, they (in the case of $N > 4$) are harder to destroy by local operations and can be regarded as an resource for the GHZ states,[11] but they are more immune to decoherence than the GHZ states.[12] The cluster states can also be used to test nonlocality without inequalities. More importantly, it has been shown that the cluster states constitute a universal resource for so-called one-way quantum computation proceeding only by local measurements and feedforward of their outcomes.[13] Thus cluster states have become an important resource in many branches of physics, especially in quantum information. The original studies on quantum entanglement focused on the systems with a finite-dimensional (discrete variable) state space. Since the experimental demonstration of quantum teleportation of coherent states,[14] much interest has arisen in continuous variable quantum information processing.[15,16] Thereupon, the entangled states with continuous variables have received much attention in the study of quantum entanglement.[17,18] Many types of continuous-variable cluster states based on different states (not coherent) have been reported in the literature.[19] A previous paper[20] has proposed and investigated the properties of the cluster-type entangled coherent states. Compared with coherent states, the squeezed vacuum states have not been investigated intensively. Actually, the squeezed states are more useful in some applications. For example, the nonclassical squeezed states of light, in which the quantum fluctuations of one quadrature are suppressed below the vacuum level, have potential applications in optical communications and gravitational detection.[21] Some of the entanglement properties of multipartite entangled squeezed vacuum states were

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discussed.[22,23] Recently, a scheme[24] for squeezed vacuum measurements without homodyning has been proposed by Wenger *et al* by following the theoretical proposal presented by Fiurášek and Cerf.[25] The schemes can be utilized to measure the squeezing and the purity of single mode squeezed vacuum state, which provides a powerful tool for the study of the squeezed vacuum state.

In this paper, we propose a scheme to prepare the CTESVS by considering the two-photon interaction between a two-level atom and a single-mode cavity with a high quality factor, driven by a strong classical field. The remainder of the paper is organized as follows. In Section 2 we prepare the squeezed vacuum state (SVS). In Section 3 we prepare the cluster-type squeezed vacuum states in four separate cavities. Finally, discussion and summary are given in Section 4.

2. The generation of squeezed vacuum state

We consider a two-photon interaction between a two-level atom with a single-mode cavity field, resonantly driven by an external classical field. The Hamiltonian of the system is given by (assuming $\hbar = 1$)[26]

$$\begin{aligned} H_{\rm s} &= \omega_0 S_z + \omega_{\rm a} a^\dagger a + g\left(a^{\dagger 2} S^- + a^2 S^+\right) \\ &\quad + \Omega\left(\mathrm{e}^{-\mathrm{i}\omega_L t} S^+ + \mathrm{e}^{\mathrm{i}\omega_L t} S^-\right), \end{aligned} \tag{1}$$

where $S_z = \frac{1}{2}(|e\rangle\langle e| - |g\rangle\langle g|)$; $S^+ = |e\rangle\langle g|$; $S^- = |g\rangle\langle e|$; $a^\dagger$ (a) is the creation (annihilation) operator of the cavity field; ω_0, $\omega_{\rm a}$ and ω_L are the atomic transition frequency, the cavity field frequency, and the classical field frequency, respectively; g and Ω are the coupling constants of atom with the cavity mode and the driving field, respectively. In the rotating frame with respect to the driving field frequency ω_L, the Hamiltonian is given by

$$\begin{aligned} H_{\rm r} &= \Delta a^\dagger a + g\left(a^{\dagger 2} S^- + a^2 S^+\right) \\ &\quad + \Omega\left(S^+ + S^-\right), \end{aligned} \tag{2}$$

where $\Delta = \omega_{\rm a} - \frac{\omega_L}{2}$. In the interaction picture, the Hamiltonian is given by

$$\begin{aligned} H_{\rm i} &= \mathrm{e}^{\mathrm{i}H_{\rm r0}t} H_{\rm ri} \mathrm{e}^{-\mathrm{i}H_{\rm r0}t} \\ &= \frac{1}{2} g\big[|+\rangle\langle +| - |-\rangle\langle -| + \mathrm{e}^{\mathrm{i}2\Omega t}|+\rangle\langle -| \\ &\quad - \mathrm{e}^{-\mathrm{i}2\Omega t}|-\rangle\langle +|\big] a^2 \mathrm{e}^{-\mathrm{i}2\Delta t} + \text{H.C.}, \end{aligned} \tag{3}$$

where

$$H_{\rm r0} = \Delta a^\dagger a + \Omega\left(S^+ + S^-\right), \tag{4}$$

$$H_{\rm ri} = g\left(a^{\dagger 2} S^- + a^2 S^+\right), \tag{5}$$

$|\pm\rangle = (|g\rangle \pm |e\rangle)/\sqrt{2}$, and $S_x|\pm\rangle = (S^+ + S^-)|\pm\rangle = \pm|\pm\rangle$. In the strong driving regime $\Omega \gg \Delta, g$, in the rotating-wave approximation the effective Hamiltonian is obtained to be

$$H_{\rm ieff} = \frac{1}{2} S_x g\left(a^{\dagger 2}\mathrm{e}^{\mathrm{i}2\Delta t} + a^2 \mathrm{e}^{-\mathrm{i}2\Delta t}\right). \tag{6}$$

If the atom-field is initially in the state $|g\rangle|0\rangle$, the total state evolves as

$$\begin{aligned} |\phi\rangle &= \mathrm{e}^{-\mathrm{i}H_{\rm ieff}t}|g\rangle|0\rangle \\ &= \mathrm{e}^{-\mathrm{i}H_{\rm ieff}t}\frac{1}{\sqrt{2}}(|+\rangle + |-\rangle)|0\rangle \\ &= \frac{1}{\sqrt{2}}\left[|+\rangle S(\xi) + |-\rangle S(-\xi)\right]|0\rangle \\ &= \frac{1}{\sqrt{2}}\left(|+\rangle|\xi\rangle + |-\rangle|-\xi\rangle\right), \end{aligned} \tag{7}$$

where

$$\begin{aligned} S(\xi) &= \mathrm{e}^{(1/2)\left(\xi^* a^2 - \xi a^{\dagger 2}\right)}, \\ \xi &= -\int_0^t \mathrm{i}g\mathrm{e}^{-\mathrm{i}2\Delta t'}\mathrm{d}t' = \frac{g(\mathrm{e}^{-\mathrm{i}2\Delta t} - 1)}{2\Delta} \end{aligned} \tag{8}$$

with $|\xi\rangle$ being the squeezed vacuum state (SVS) of the cavity mode.

3. The generation of cluster-type entangled squeezed vacuum states

Now we discuss how to prepare the four-cavity CTESVS. The experimental setup is shown in Fig.1.

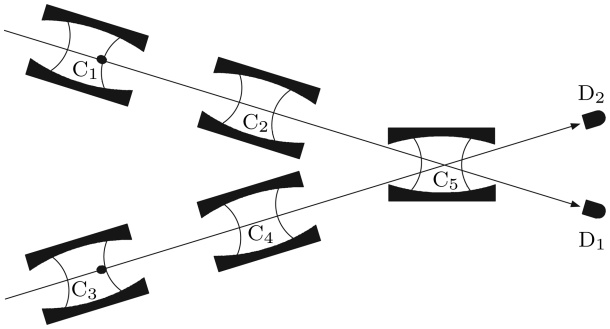


Fig.1. Sketch of the proposed experimental setup. Each flying atom crosses two cavities. Both atoms enter the fifth cavity which is to apply a quantum phase gate between the atoms before measurement to D_1 and D_2.

Assume four identical cavities C_1, C_2, C_3 and C_4 to be initially in vacuum states $|0_1\rangle, |0_2\rangle, |0_3\rangle$ and $|0_4\rangle$, respectively and two identical two-level atoms initially prepared in the state $|g_1\rangle|g_2\rangle$, and then the initial state of the whole system will be

$$|\psi_0\rangle = |g_1\rangle|g_2\rangle|0_1\rangle|0_2\rangle|0_3\rangle|0_4\rangle. \tag{9}$$

Atom 1 crosses cavities C_1 and C_2 in sequence and atom 2 crosses cavities C_3 and C_4. After an interaction time t in each of two cavities atom i $(i = 1, 2)$ and respective cavities stay in the state

$$|\psi_i\rangle = \frac{1}{\sqrt{2}}(|+\rangle_i|\xi\rangle|\xi\rangle + |-\rangle_i|-\xi\rangle|-\xi\rangle), \quad (i = 1, 2). \tag{10}$$

Hence, the state of the whole system is given by

$$\begin{aligned}|\psi\rangle &= |\psi_1\rangle \otimes |\psi_2\rangle \\ &= \frac{1}{2}(|++\rangle|\xi,\xi\rangle_{12}|\xi,\xi\rangle_{34} \\ &\quad +|+-\rangle|\xi,\xi\rangle_{12}|-\xi,-\xi\rangle_{34} \\ &\quad +|-+\rangle|-\xi,-\xi\rangle_{12}|\xi,\xi\rangle_{34} \\ &\quad +|--\rangle|-\xi,-\xi\rangle_{12}|-\xi,-\xi\rangle_{34}).\end{aligned} \tag{11}$$

In order to achieve the CTESVS, we need now to perform a controlled phase gate (CPG) operation on the atomic dressed basis $|\pm\rangle = \frac{1}{\sqrt{2}}(|g\rangle \pm |e\rangle)$ before atomic state measurement. The quantum phase gate between the atoms may be implemented by using the fifth cavity (see Fig.1). The atoms will now simultaneously interact with both the cavity field in the fifth cavity and an external classical field. By using the rotation wave approximation, the Hamiltonian for the system can be written as (assuming $\hbar = 1$)[27]

$$\begin{aligned}H_{\rm f} = &\sum_{i=1}^{2}\omega_0 S_{z,i} + \omega_{\rm a}a^{\dagger}a + \sum_{i=1}^{2}\Big[g'\left(a^{\dagger}S_i^- + aS_i^+\right) \\ &+\Omega\left(\mathrm{e}^{-\mathrm{i}\omega_L t}S_i^+ + \mathrm{e}^{\mathrm{i}\omega_L t}S_i^-\right)\Big],\end{aligned} \tag{12}$$

where $S_{z,i} = \frac{1}{2}(|e_i\rangle\langle e_i| - |g_i\rangle\langle g_i|)$, $S_i^+ = |e_i\rangle\langle g_i|$, and $S_i^- = |g_i\rangle\langle e_i|$, $(i = 1, 2)$; g' is the atom–cavity coupling constant, with $\omega_0 = \omega_L$ assumed. In the strong driving regime $\Omega \gg \{g', \delta\}$, the interaction Hamiltonian is written as[28,29]

$$H_{\rm f}^{\rm I} = \frac{1}{2}\sum_{i=1}^{2} g'\left(a\mathrm{e}^{\mathrm{i}\delta t} + a^{\dagger}\mathrm{e}^{-\mathrm{i}\delta t}\right)\left(S_i^+ + S_i^-\right), \tag{13}$$

where $\delta = \omega_0 - \omega_{\rm a}$ is the detuning between the frequencies of the cavity field and atoms. In the case $\delta \gg g'/2$, there is no energy exchange between the atomic system and the cavity. The strong classical field causes photon-number-dependent Stark shifts to be cancelled. Then the effective Hamiltonian is given by[28]

$$\begin{aligned}H_{\rm f}^{\rm eff} = &\Omega\sum_{i=1}^{2}\left(S_i^+ + S_i^-\right) + \lambda\Bigg[\frac{1}{2}\sum_{i=1}^{2}(|e_i\rangle\langle e_i| \\ &+|g_i\rangle\langle g_i|) + \sum_{i,j=1}^{2}\left(S_i^+S_j^+ + S_i^+S_j^- + \text{H.C.}\right)\Bigg], \\ &i \neq j,\end{aligned} \tag{14}$$

where $\lambda = g'^2/2\delta$. So we can use this Hamiltonian to perform the CPG. We choose the interaction time $t_{\rm f}$ and Rabi frequency Ω appropriately such that $t_{\rm f} = \pi/4\lambda$ and $t_{\rm f} = \left(2k + \frac{1}{4}\right)\pi/\Omega$ (integer $k > 1$) between the atoms and the cavity field. Then the following transformation is performed:[20]

$$\begin{aligned}\hat{U}_{\rm CPG}|++\rangle &= -|++\rangle, \\ \hat{U}_{\rm CPG}|+-\rangle &= |+-\rangle, \\ \hat{U}_{\rm CPG}|-+\rangle &= |-+\rangle, \\ \hat{U}_{\rm CPG}|--\rangle &= |--\rangle,\end{aligned} \tag{15}$$

where $\hat{U}_{\rm CPG} = \exp(-\mathrm{i}H_{\rm f}^{\rm eff}t_{\rm f})$. The $\hat{U}_{\rm CPG}$ causes Eq.(11) to evolve to

$$\begin{aligned}|\psi'\rangle = &\frac{1}{2}(-|++\rangle|\xi,\xi\rangle_{12}|\xi,\xi\rangle_{34} \\ &+|+-\rangle|\xi,\xi\rangle_{12}|-\xi,-\xi\rangle_{34} \\ &+|-+\rangle|-\xi,-\xi\rangle_{12}|\xi,\xi\rangle_{34} \\ &+|--\rangle|-\xi,-\xi\rangle_{12}|-\xi,-\xi\rangle_{34}).\end{aligned} \tag{16}$$

Equation (16) can be rewritten as

$$\begin{aligned}|\psi'\rangle = &\frac{1}{4}[|gg\rangle(|\xi,\xi\rangle_{12}\sigma_{34} + |-\xi,-\xi\rangle_{12})(|\xi,\xi\rangle_{34} \\ &+|-\xi,-\xi\rangle_{34}) + |ge\rangle(|\xi,\xi\rangle_{12}\sigma_{34} \\ &+|-\xi,-\xi\rangle_{12})(|\xi,\xi\rangle_{34} - |-\xi,-\xi\rangle_{34}) \\ &+|eg\rangle(|\xi,\xi\rangle_{12}\sigma_{34} - |-\xi,-\xi\rangle_{12})(|\xi,\xi\rangle_{34} \\ &+|-\xi,-\xi\rangle_{34}) + |ee\rangle(|\xi,\xi\rangle_{12}\sigma_{34} \\ &-|-\xi,-\xi\rangle_{12})(|\xi,\xi\rangle_{34} - |-\xi,-\xi\rangle_{34})]\ ,\end{aligned} \tag{17}$$

with $\sigma_{34} = -|\xi,\xi\rangle_{34}\langle\xi,\xi| + |-\xi,-\xi\rangle_{34}\langle-\xi,-\xi|$.

The final atomic states are analysed in the state-selective field-ionization detectors D_1 and D_2 (see Fig.1), respectively. Depending on the detection results of the atomic states, the four-cavity fields are projected onto one of the four CTESVS as follows:

$$\begin{aligned}|gg\rangle \rightarrow &(|\xi,\xi\rangle_{12}\sigma_{34} + |-\xi,-\xi\rangle_{12})(|\xi,\xi\rangle_{34} \\ &+|-\xi,-\xi\rangle_{34}),\end{aligned}$$

$$
\begin{aligned}
|ge\rangle &\rightarrow (|\xi,\xi\rangle_{12}\sigma_{34}+|-\xi,-\xi\rangle_{12})(|\xi,\xi\rangle_{34}\\
&\quad -|-\xi,-\xi\rangle_{34}),\\
|eg\rangle &\rightarrow (|\xi,\xi\rangle_{12}\sigma_{34}-|-\xi,-\xi\rangle_{12})(|\xi,\xi\rangle_{34}\\
&\quad +|-\xi,-\xi\rangle_{34}),\\
|ee\rangle &\rightarrow (|\xi,\xi\rangle_{12}\sigma_{34}-|-\xi,-\xi\rangle_{12})(|\xi,\xi\rangle_{34}\\
&\quad -|-\xi,-\xi\rangle_{34}). \qquad (18)
\end{aligned}
$$

4. Discussion and summary

We now give a brief discussion about the feasibility for the proposed scheme. From Refs.[30,31], the coupling constant of the two-photon interaction can be taken as $g/2\pi = 1\,\mathrm{kHz}$, about 1/50 that of the single-photon interaction ($2\pi \times 49\,\mathrm{kHz}$).[26] Therefore, if $\Omega/2\pi = 1\,\mathrm{MHz}$, the condition ($\Omega \gg \Delta, g$) of the rotating-approximation in expression (6) is satisfied. A photon storage time in the cavity is $T_\mathrm{r} \simeq 130\,\mathrm{ms}$, and the lifetime of the circular Rydberg atom is $T_\mathrm{a} \simeq 30\,\mathrm{ms}$,[20] much longer than the cavity mode decay time $T_\mathrm{cav} \simeq 0.85\,\mathrm{ms}$.[32] So we will consider only the cavity decay. For the cavity with the size $L = 27.5\,\mathrm{mm}$ and the waist of Gaussian field mode $w = 6\,\mathrm{mm}$,[31] if the atoms move with the speed $\upsilon = 200\,\mathrm{m/s}$,[32] the interaction time of each atom with the cavity mode is about $T_\mathrm{i} = \sqrt{\pi}w/\upsilon = 5.3 \times 10^{-2}\,\mathrm{ms}$, and the time for the atoms to cross the cavity is about $T_\mathrm{t} = 0.14\,\mathrm{ms}$. Having neglected the spacing between the cavities, the generation protocol takes a time $T = 2T_\mathrm{i} + 3T_\mathrm{t} + \pi/4\lambda$, which for $g' = 2\pi \times 49\,\mathrm{kHZ}$, and $\delta = 2\pi \times 8g'$, gives $T \simeq 0.786\,\mathrm{ms}$, shorter than T_cav. But in current optical cavity QED systems, the coupling strength $g(\boldsymbol{r})$ of atoms with the cavity modes depends on the atomic position $\boldsymbol{r}$. If atomic motion is localized within a size (δr) comparable with the cavity mode resonant wavelength λ_c, this position-dependent uncertainty generally reduces the quantum coherence or entanglement between atoms and cavity modes. It requires the Lamb–Dicke limit $\delta r \ll \lambda_\mathrm{c}$ to be imposed on an approximate coupling constant g. This requirement has been met in a one-cavity system, and can be obtained by atom-cooling techniques. However, our scheme needs atoms to cross three cavities separated by a distance L with a speed v, and in each cavity, the Lamb–Dicke limit is required to repress the decoherence caused by atomic motion. If the initial wave packet has a size δr, according to the Heisenberg uncertainty principle, the atomic size will be uncertain by a quantity $d = [h/m(\delta r)]^*(L/v)$ (m is the mass of the atom and h is the Planck's constant).[33] To assure that the Lamb–Dicke limit is still effective, the uncertain quantity d should be much less than the wave size δr, i.e. $d \ll \delta r$. This leads to more stringent conditions on the experimental parameters than one-cavity case. Therefore, the effect of the atomic motion on the scheme needs further studying.

In summary, we have proposed a scheme to prepare the CTESVS based on the two-photon Jaynes–Cumming (JC) model, driven by a strong classical field. After the realization of simple atomic measurements, the generation of CTESVS in four separate cavities is accomplished within the cavity decay time. In the case of large atom-cavity detuning, the scheme is immune to the effect of atomic spontaneous emission.

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