Scheme for generating a cluster-type entangled squeezed vacuum state via cavity QED*

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A scheme is proposed to generate an N-qubit cluster-type entangled squeezed vacuum state (CTESVS) based on the two-photon interaction between a two-level atom and the cavity fields with the cavity QED system. The CTESVS in N separate cavities can be effectively obtained after performing a simple one-qubit measurement on the atom. The influence of cavity decay on the CTESVS is also discussed.

Keywords: cluster state, squeezed vacuum state, quantum entanglement, cavity QED

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1. Introduction

Quantum entanglement, as one of the most characteristic features of quantum states, is not only widely used for applications to quantum information theory and quantum computation,[1–12] but also opens up possibilities for the testing of quantum nonlocality.[13,14] Compared with bipartite entanglement,[15] multipartite entanglement[16–20] has a more complex structure and various types that may play an important role in quantum computation and communication networks. In particular, cluster states,[16] first introduced by Briegel and Raussendorf, have some special features. They have a large persistence of entanglement, that is, they (in the case of $N > 4$) are harder to destroy by local operations and can be regarded as a resource for the GHZ (Greenberger–Horne–Zeilinger) states, but they are more immune to decoherence than the GHZ states.[19] In addition, they are not only fundamental resources for the linear optics one-way quantum computation,[21] but also for quantum error correction,[22] quantum communication protocols,[23] and fundamental tests of non-locality.[24] So cluster states have attracted much attention recently and many theoretical schemes for generating them have been proposed in different physical systems, such as photons,[25–27] cavity QED,[28–30] trapped ions,[31] and so on.[32,33] And some experimental realizations have also been reported.[34–37]

Up to now, many types of continuous-variable cluster states based on different states have been reported in the literature.[38–47] For example, Munhoz *et al.*[40] proposed a scheme of the generation of four-qubit cluster-type entangled coherent states and investigated the properties of the cluster-type entangled coherent states based on the off-resonant interaction between two identical two-level atoms and four cavitives. Yang *et al.*[42] proposed a simplified scheme of the generation of four-qubit cluster-type entangled coherent states based on resonant interaction of a two-mode cavity with a two-level atom driven by strong classical fields. An *et al.*[44] proposed a simple efficient scheme of the generation of cluster-type entangled coherent states with all the modes flying freely in space using only one π-cross-Kerr medium combined with linear optics elements. In addition, Fan *et al.*[45] proposed a scheme of the generation of cluster-type entangled coherent states based on the off-resonant interaction between one three-level atom and N cavities. We also proposed a scheme of the generation of four-qubit CTESVS based on the two-photon interaction between two atoms and four cavities.[47]

In this paper, we propose a scheme to generate CTESVS based on a two-photon interaction between one two-level atom and N vacuum cavities, assisted by the strong driving fields. In our scheme, no two-qubit quantum phase gate operation is necessary and only one atom needs to be measured. Moreover, the CTESVS under the cavity decay is also considered. This paper is organized as follows: in Section 2, we propose a scheme to generate an ideal cluster-type squeezed vacuum state of many cavities. In Section 3, we consider the effect of the cavity decay on the preparation of the cluster-type squeezed vacuum state. In Section 4, the experimental feasibility of the proposed scheme is briefly discussed. A summary is given in the last section.

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2. Generation of an ideal cluster-type entangled squeezed vacuum state

In this section, we show how to generate a cluster-type entangled squeezed vacuum state of many cavities. We consider a two-level atom in a two-photon interaction with a single-mode cavity field, driven by an external classical field. The Hamiltonian of the system in the Schrödinger picture is given by[48]

$$\begin{aligned} H_{\rm s} &= \frac{1}{2}\omega_0(|e\rangle\langle e| - |g\rangle\langle g|) + \omega_{\rm c} a^{\dagger} a \\ &\quad + (g a^{\dagger 2}|g\rangle\langle e| + \Omega\, {\rm e}^{-{\rm i}\omega_{\rm L} t}|e\rangle\langle g| + {\rm H.c.}), \end{aligned} \tag{1}$$

where ω_0, $\omega_{\rm c}$, $\omega_{\rm L}$ are the frequencies of the atomic resonant transition, the cavity mode, and the classical field, respectively; $a^{\dagger}$ (a) is the creation (annihilation) operator of the cavity mode; Ω and g are the coupling constants of the atom to the classical field and to the cavity mode. In the strong driving regime, the effective Hamiltonian in the rotating-wave approximation is written as[48]

$$H_{\rm eff} = \frac{g}{2}(|+\rangle\langle +| - |-\rangle\langle -|)\left(a^{\dagger 2}{\rm e}^{{\rm i}2\delta t} + a^2 {\rm e}^{-{\rm i}2\delta t}\right), \tag{2}$$

where $|\pm\rangle = (|g\rangle \pm |e\rangle)/\sqrt{2}$ and $\delta = \omega_{\rm c} - \omega_{\rm L}/2$. If the atom-field is initially in the state $|g\rangle|0\rangle$, the total state evolves to

$$\begin{aligned} |\varphi\rangle &= {\rm e}^{-{\rm i}H_{\rm eff}t}|g\rangle|0\rangle \\ &= {\rm e}^{-{\rm i}H_{\rm eff}t}\frac{1}{\sqrt{2}}(|+\rangle + |-\rangle)|0\rangle \\ &= [|+\rangle S(\xi) + |-\rangle S(-\xi)]|0\rangle \\ &= \frac{1}{\sqrt{2}}(|+\rangle|\xi\rangle + |-\rangle|-\xi\rangle), \end{aligned} \tag{3}$$

where

$$\begin{aligned} S(\xi) &= {\rm e}^{(1/2)\left(\xi^* a^2 - \xi a^{\dagger 2}\right)}, \\ \xi &= -\int_0^t {\rm i}g{\rm e}^{-{\rm i}2\delta t'}\,{\rm d}t' = \frac{g({\rm e}^{-{\rm i}2\delta t} - 1)}{2\delta}, \end{aligned} \tag{4}$$

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

We now describe the process of preparing N-qubit CTESVS in detail. The experimental setup is shown in Fig. 1. We assume that the atom is initially in the ground state $|g\rangle$ and all cavities are in the vacuum state $|0\rangle$. Then, the initial state of the whole system is

$$|\psi_0\rangle = |g\rangle|0\rangle_1|0\rangle_2\cdots|0\rangle_N. \tag{5}$$

First, we let the atom cross the first cavity C_1, making the atom interact with the cavity C_1 governed by the evolution process in Eq. (3). After the interaction time t, the state of the whole system becomes

$$\begin{aligned} |\psi_1\rangle &= [|+\rangle S(\xi) + |-\rangle S(-\xi)]|0\rangle_1|0\rangle_2\cdots|0\rangle_N \\ &= \frac{1}{\sqrt{2}}(|+\rangle|\xi\rangle_1 + |-\rangle|-\xi\rangle_1)|0\rangle_2\cdots|0\rangle_N. \end{aligned} \tag{6}$$

Then we let the atom cross the Ramsey zones R_1 and interact with the classical field resonant to the atomic transition, with the intensity adjusted to produce a $\theta = \pi/4$ rotation in the atomic space, i.e.,

$$|+\rangle \to \frac{1}{\sqrt{2}}(|+\rangle + |-\rangle),\ \ |-\rangle \to \frac{1}{\sqrt{2}}(|+\rangle - |-\rangle), \tag{7}$$

where

$$R_i(\theta) = {\rm e}^{{\rm i}\pi/2} R_z(\theta) R_x(\theta) R_z(\theta), \tag{8}$$

with

$$\begin{aligned} R_x(\theta) &= \begin{pmatrix} \cos\theta & -{\rm i}\sin\theta \\ -{\rm i}\sin\theta & \cos\theta \end{pmatrix}, \\ R_z(\theta) &= \begin{pmatrix} {\rm e}^{-{\rm i}\theta} & 0 \\ 0 & {\rm e}^{{\rm i}\theta} \end{pmatrix}. \end{aligned} \tag{9}$$

Thus equation (6) becomes

$$\begin{aligned} |\psi_1'\rangle &= \frac{1}{2}[|+\rangle(|\xi\rangle_1 + |-\xi\rangle_1) + |-\rangle(|\xi\rangle_1 - |-\xi\rangle_1)] \\ &\quad \times |0\rangle_2\cdots|0\rangle_N \\ &= \frac{1}{2}(|+\rangle + |-\rangle\sigma_1)(|\xi\rangle_1 + |-\xi\rangle_1)|0\rangle_2\cdots|0\rangle_N, \end{aligned} \tag{10}$$

where σ_1 is a formal symbol (not a real unitary operation) to be understood by the convention $\sigma_1|\pm\xi\rangle_1 \to \pm|\pm\xi\rangle_1$.

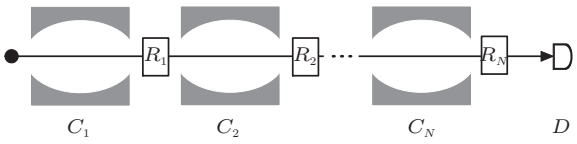


Fig. 1. Schematic setup to generate the cluster-type entangled squeezed vacuum state. An atom enters all cavities C_i and Ramsey zones R_i, respectively, and is finally measured by detector D.

Next, in the same way, we let the atom cross through the C_2 and R_2, then the state of the whole system is given by

$$\begin{aligned} |\psi_2\rangle &= \frac{1}{2\sqrt{2}}[|+\rangle(|\xi\rangle_2 + |-\xi\rangle_2\sigma_1) + |-\rangle(|\xi\rangle_2 - |-\xi\rangle_2\sigma_1)] \\ &\quad \otimes(|\xi\rangle_1 + |-\xi\rangle_1)|0\rangle_3\cdots|0\rangle_N \\ &= \frac{1}{2\sqrt{2}}(|+\rangle + |-\rangle\sigma_2)(|\xi\rangle_2 + |-\xi\rangle_2\sigma_1) \\ &\quad \times (|\xi\rangle_1 + |-\xi\rangle_1)|0\rangle_3\cdots|0\rangle_N. \end{aligned} \tag{11}$$

Subsequently, we let the atom cross through C_3, R_3, C_4, R_4, …, C_N, R_N, respectively, in the same way. Then the state of the whole system becomes

$$\begin{aligned} |\psi_N\rangle &= \frac{1}{2^{(N+1)/2}}(|+\rangle + |-\rangle\sigma_N)(|\xi\rangle_N + |-\xi\rangle_N\sigma_{N-1}) \\ &\quad \otimes(|\xi\rangle_{N-1} + |-\xi\rangle_{N-1}\sigma_{N-2})\cdots \\ &\quad \times (|\xi\rangle_2 + |-\xi\rangle_2\sigma_1)(|\xi\rangle_1 + |-\xi\rangle_1). \end{aligned} \tag{12}$$

We now detect the atomic state in the basis $\{|+\rangle, |-\rangle\}$. If the result is $|+\rangle$, the total state collapses into

$$\begin{aligned}|\text{Cluster}\rangle_1 &= \frac{1}{2^{N/2}}(|\xi\rangle_N + |-\xi\rangle_N\sigma_{N-1}) \\ &\times (|\xi\rangle_{N-1} + |-\xi\rangle_{N-1}\sigma_{N-2}) \\ &\otimes \cdots (|\xi\rangle_2 + |-\xi\rangle_2\sigma_1)(|\xi\rangle_1 + |-\xi\rangle_1), \end{aligned} \quad (13)$$

which is an N-mode CTESVS. While for the result $|-\rangle$, the total state collapses into

$$\begin{aligned}|\text{Cluster}\rangle_2 &= \frac{1}{2^{N/2}}\sigma_N(|\xi\rangle_N + |-\xi\rangle_N\sigma_{N-1}) \\ &\times (|\xi\rangle_{N-1} + |-\xi\rangle_{N-1}\sigma_{N-2}) \\ &\otimes \ldots (|\xi\rangle_2 + |-\xi\rangle_2\sigma_1)(|\xi\rangle_1 + |-\xi\rangle_1). \end{aligned} \quad (14)$$

3. Cluster-type entangled squeezed vacuum state under the cavity decay

In this section, we consider the effect of the cavity decay on the CTESVS. The Hamiltonian of the system of Eq. (1) can be rewritten as

$$\begin{aligned}H_s' &= \frac{1}{2}\omega_0(|e\rangle\langle e| - |g\rangle\langle g|) + \omega_c a^\dagger a \\ &+ (g a^{\dagger 2}|g\rangle\langle e| + \Omega e^{-i\omega_L t}|e\rangle\langle g| + \text{H.c.}) - i\frac{\kappa}{2}a^\dagger a, \end{aligned} \quad (15)$$

where κ is the cavity decay rate. Under the same conditions, the effective Hamiltonian in Eq. (2) becomes

$$\begin{aligned}H_{\text{eff}}' &= \frac{g}{2}(|+\rangle\langle +| - |-\rangle\langle -|) \\ &\times \left(a^{\dagger 2} e^{i2\delta t} e^{\kappa t} + a^2 e^{-i2\delta t} e^{-\kappa t}\right). \end{aligned} \quad (16)$$

In this case, the time-dependent squeezing parameter in Eqs. (3) and (4) becomes

$$\xi' = \frac{g(2\delta - i\kappa)(e^{-i2\delta t}e^{-\kappa t} - 1)}{4\delta^2 + \kappa^2}. \quad (17)$$

We plot the squeezing degree ξ' versus both t and the ratio of κ/δ according to Eq. (17), as shown in Fig. 2, where we have assumed $\delta = g = 2\pi$ kHz.[48] From Fig. 2 we can see that when $\kappa = 0$, the squeeze parameter exhibits a standard periodical evolution. However, the evolution of $|\xi'|$ gradually deviates from the periodical variation with the increase of ratio κ/δ. This indicates that the cavity is unable to return to the initial state precisely because of the increase of cavity decay. To avoid this situation, our scheme is restricted to the condition of $\kappa \ll \delta$ for realizing N-qubit CTESVS.

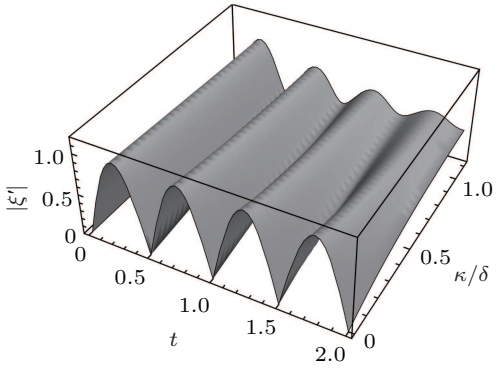


Fig. 2. The evolution of the squeeze parameter ξ' with both time t and ratio κ/δ under the cavity decay, where we have set $\delta = g = 2\pi$ kHz.

4. Discussion

We now briefly discuss the experimental feasibility of the proposed scheme in an actual system consisting of a Rydberg atom and microwave cavities. Fortunately, in our scheme, the effect of atomic spontaneous emission can be ignored by virtue of the large atom–cavity detuning. In addition, we also consider the lifetimes of the atom and cavities. A photon storage time in each cavity is $T_p \simeq 130$ ms and the cavity mode decay time is $T_c \simeq 100$ ms,[49] which are much longer than the lifetime of the circular Rydberg atom $T_a \simeq 30$ ms.[50] For the cavity with the size $L = 27.5$ mm and the waist of the Gaussian field mode $w = 6$ mm,[50] if the atomic velocity is $v = 200$ m/s,[51] the interaction time of the atom with each cavity mode is about $T_i = \sqrt{\pi}w/v = 5.317 \times 10^{-2}$ ms, and the time of the atom crossing each cavity is about $t_i \simeq 0.14$ ms. So we can obtain the squeezing degree $|\xi| = \sqrt{[1 - \cos(2\delta T_i)]/2} \simeq 0.33$. If the time of the atom crossing one Ramsey zone is about $T_R \simeq 10^{-5}$ ms,[45] the required time of the generation of a ten-qubit cluster-type entangled squeezed vacuum state is about $T = 10 \times (t_i + T_i + T_R) \simeq 1.93$ ms, which is much shorter than T_a. If the cavity decay is considered, we can take $\kappa = g/27$.[52] In this case we have $\kappa/|\delta| \simeq 0.069$ for the time $t = \pi/\sigma$ or $\kappa/\delta \simeq 0.037$ for $g = \delta$ from Eqs. (4) and (17), so the condition $\kappa \ll \delta$ is satisfied approximately. Then the interaction time of the atom with each cavity mode is about $T_\kappa \simeq 1.3$ ms or $T_\kappa \simeq 5.318 \times 10^{-2}$ ms, which is also much shorter than T_a and T_c. We also compare our proposal with the previous one.[47] In Ref. [47], four-qubit CTESVS can be prepared via use of five QED cavities, two Rydberg atoms, and two atomic ionization detectors. Each flying atom crossed two cavities in sequence, respectively. After that, two atoms simultaneously entered the fifth cavity, which is to apply a quantum phase gate between the atoms before two atomic measurements. So we can see that to achieve the four-qubit CTESVS, the auxiliary caivty is used to implement the controlled phase gate and two atoms are simultaneously measured with two detectors. In contrast, as shown above, our present scheme needs only one atom to interact with N cavities to generate the N-qubit CTESVS with a

simple one-qubit measurement on the atom. Hence, the physical resources and the controlled phase gate are reduced. In addition, the Lamb–Dick limit of the ground state of axial motion has been demonstrated in a recent experiment for a single trapped atom strongly coupled to the field of a high finesse optical resonator.[53] However, our scheme needs an atom to pass through N cavities separated by a distance Z with a longitudinal velocity v, and in each cavity, the Lamb–Dick limit is required to suppress the decoherence caused by the atomic motion. It leads to more stringent conditions on the experimental parameters than a one-cavity case. Therefore, the influence of the atomic motion on the scheme needs to be further studied.

5. Summary

In summary, we have proposed a scheme to generate an N-qubit cluster-type entangled squeezed vacuum state based on a two-photon interaction between one two-level atom and N vacuum cavity fields. Compared with the scheme of Ref. [47], we just use one atom to interact with N cavities, and the two-qubit quantum phase gate operation is not necessary. In our scheme, the generation of N-qubit CTESVS in N separate cavities is achieved by using the simple one-atomic measurement. Because of the large atom–cavity detuning, the scheme is immune to the effect of atomic spontaneous emission. In addition, to ensure the effectiveness of the scheme, the condition $\kappa \ll \delta$ must be satisfied.

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