Preparation of the four-qubit cluster states in cavity QED and the trapped-ion system*

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This paper proposes a simple scheme to generate a four-atom entangled cluster state in cavity quantum electrodynamics. With the assistantce of a strong classical field the cavity is only virtually excited and no quantum information will be transferred from the atoms to the cavity during the preparation for a four-atom entangled cluster state, and thus the scheme is insensitive to the cavity field states and cavity decay. Assuming that deviation of laser intensity is 0.01 and that of simultaneity for the interaction is 0.01, it shows that the fidelity of the resulting four-atom entangled cluster state is about 0.9886. The scheme can also be used to generate a four-ion entangled cluster state in a hot trapped-ion system. Assuming that deviation of laser intensity is 0.01, it shows that the fidelity of the resulting four-ion entangled cluster state is about 0.9990. Experimental feasibility for achieving this scheme is also discussed.

Keywords: cavity quantum electrodynamics (QED), trapped ions, cluster state
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Quantum entanglement is one of the most striking features of quantum mechanics.[1] Entangled states of three or more particles not only provide possibilities to test quantum mechanics against local hidden theory without using inequality,[2] but also has many practical applications in quantum information processing, such as quantum teleportation,[3] quantum entanglement swapping,[4] and quantum dense coding.[5] Hence, quantum entanglement has been viewed as an essential resource for quantum information processing and it is of importance for exploring and preparing entangled states, especially multipartite entanglement. It has been shown that there are three inequivalent classes of multipartite entanglement states, the Greenberger-Horne-Zeilinger (GHZ) class,[6] the W class[7] and cluster class states,[8] under stochastic local operation and classical communication. While the cluster states introduced by Briegel and Raussendor[8] can be regarded as a resource for GHZ states and are more immune to decoherence than GHZ states.[9,10] On the other hand, it has been shown that quantum computer can be realized via cluster states.[9] The proof of Bell's theorem without the inequality was given for cluster states,[10] and Bell inequality is maximally violated by the four-qubit cluster state and is not violated by the four-qubit GHZ state. Because of these advantages, cluster states have attracted much attention recently and various schemes for generating them via different physical systems, especially the cavity quantum electrodynamics (QED) system, have been proposed.[11−18] In Ref. [17], Yang *et al.* propose a scheme for preparing a four-atom cluster state in a thermal cavity QED, but their scheme includes two single-qubit operations and four two-qubit operations, while our scheme only includes two three-qubit operations. In the other Refs. [11]–[15], [18], the schemes for preparing a four-qubit cluster state require at least three steps. It is known that the more the operation steps, the longer the operational time of the state preparation, because there exists the delay time between any two neighbouring operations in actual experiments. In Ref. [16], Ye *et al.* proposed a cavity QED scheme for generating a four-atom cluster state. Their scheme is very simple. However, recently Ye and Guo have admitted[19] that the third term of Eq. [19] in Ref. [16] has a sign error because of their carelessness and this mistake makes the scheme impossible for generating a four-atom entangled cluster state. Here

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we propose a simple scheme to generate a four-atom entangled cluster state in cavity QED. With the assistance of a strong classical field the cavity is only virtually excited and no quantum information will be transferred from the atoms to the cavity during the preparation for a four-atom entangled cluster state, and thus the scheme is insensitive to the cavity field states and cavity decay. The scheme can also be used to generate a four-ion entangled cluster state in hot trapped-ion system.

We consider N identical two-level atoms simultaneously interacting with a single-mode cavity field, at the same time the atoms are driven by a classical field. Assume that the frequency of driving field ω is equal to the atomic transition frequency ω_0. In the strong driving regime $2\Omega \gg \delta$, $g/2$(Ω is the Rabi frequency of the classical field, g is the atoms-cavity coupling strength and δ is the detuning between the atomic transition frequency and the cavity field frequency), we can neglect the terms oscillating fast. In the large detuning $\delta \gg g/2$, there is no energy exchange between the atomic system and the cavity. Then the effective Hamiltonian can be described by[20]

$$H_{\rm eff} = 2(\Omega S_x + \lambda S_x^2), \tag{1}$$

where $\lambda = g^2/(2\delta)$, $S_x = \sum_{j=1}^{N}(S_j^+ + S_j^-)/2$, and $S_j^+ = |e\rangle_j\langle g|$, $S_j^- = |g\rangle_j\langle e|$, with $|e\rangle_j$ and $|g\rangle_j$ being the excited and ground states of the jth atom. We note that the effective Hamiltonian is independent of the cavity field state, allowing it to be in a thermal state. In addition, there is no exchange of energy between the atoms and the cavity mode. So the effects of the cavity decay and the thermal field are all eliminated. Then the evolution operator of the system is given by

$$U(t) = {\rm e}^{-{\rm i}H_{\rm eff}t} = {\rm e}^{-{\rm i}2(\Omega S_x + \lambda S_x^2)t}. \tag{2}$$

If three atoms, which that are initially in the state $|x_1x_2x_3\rangle$, are simultaneously sent into the cavity, and they are driven by a classical field, then the state of three atoms will evolve into

$$\begin{aligned}|x_1x_2x_3\rangle \longrightarrow\ & {\rm e}^{-5\lambda t{\rm i}/2}\{\cos(2\lambda t)(\cos(\Omega t)|x_1\rangle - {\rm i}\sin(\Omega t)|\bar{x}_1\rangle)(\cos(\Omega t)|x_2\rangle - {\rm i}\sin(\Omega t)|\bar{x}_2\rangle)(\cos(\Omega t)|x_3\rangle \\ & -{\rm i}\sin(\Omega t)|\bar{x}_3\rangle) + \frac{\rm i}{2}\sin(2\lambda t)[(\cos(\Omega t)|x_1\rangle - {\rm i}\sin(\Omega t)|\bar{x}_1\rangle)(\cos(\Omega t)|x_2\rangle \\ & -{\rm i}\sin(\Omega t)|\bar{x}_2\rangle)(\cos(\Omega t)|x_3\rangle - {\rm i}\sin(\Omega t)|\bar{x}_3\rangle) - (\cos(\Omega t)|\bar{x}_1\rangle - {\rm i}\sin(\Omega t)|x_1\rangle)(\cos(\Omega t)|\bar{x}_2\rangle \\ & -{\rm i}\sin(\Omega t)|x_2\rangle)(\cos(\Omega t)|x_3\rangle - {\rm i}\sin(\Omega t)|\bar{x}_3\rangle) - (\cos(\Omega t)|\bar{x}_1\rangle - {\rm i}\sin(\Omega t)|x_1\rangle)(\cos(\Omega t)|x_2\rangle \\ & -{\rm i}\sin(\Omega t)|\bar{x}_2\rangle)(\cos(\Omega t)|\bar{x}_3\rangle - {\rm i}\sin(\Omega t)|x_3\rangle) - (\cos(\Omega t)|x_1\rangle - {\rm i}\sin(\Omega t)|\bar{x}_1\rangle)(\cos(\Omega t)|\bar{x}_2\rangle \\ & -{\rm i}\sin(\Omega t)|x_2\rangle)(\cos(\Omega t)|\bar{x}_3\rangle - {\rm i}\sin(\Omega t)|x_3\rangle)]\},\end{aligned} \tag{3}$$

where $x \in \{g, e\}$ and $\bar{x}$ is the counterpart of the binary number x. Choosing $\lambda t = \pi/4$ and realising the condition $(\Omega t) = n\pi(n = 1, 2\ldots)$ by modulating the driving field appropriately, we find that the state of three atoms evolves into

$$|x_1x_2x_3\rangle \longrightarrow \frac{(-1)^n{\rm i}}{2}\,{\rm e}^{-5\pi{\rm i}/8}(|x_1x_2x_3\rangle - |\bar{x}_1\bar{x}_2x_3\rangle - |\bar{x}_1x_2\bar{x}_3\rangle - |x_1\bar{x}_2\bar{x}_3\rangle). \tag{4}$$

For generating the four-atom entangled cluster state, we assume that four atoms are initially in the state $|g_1g_2g_3g_4\rangle$. First, the atoms 2, 3, and 4 are simultaneously sent into the cavity C_1 and simultaneously interact with a single-mode cavity field. At the same time, they are driven by a classical field. After the interaction time which satisfies $\lambda t_1 = \pi/4$ and $(\Omega t)_1 = n\pi(n = 1, 2\ldots)$, the state of the system evolves into

$$|\psi_1\rangle = \frac{(-1)^n{\rm i}}{2}\,{\rm e}^{-5\pi{\rm i}/8}|g_1\rangle(|g_2g_3g_4\rangle - |e_2e_3g_4\rangle - |e_2g_3e_4\rangle - |g_2e_3e_4\rangle). \tag{5}$$

After atoms 2, 3, and 4 exit from the cavity C_1, the atoms 1, 2, and 3 are simultaneously sent into the cavity C_2. At the same time, they are driven by a classical field. After the interaction time which satisfies $\lambda t_2 = \pi/4$ and $(\Omega t)_2 = n\pi(n = 1, 2\ldots)$, the state of the system evolves into

$$\begin{aligned}|\psi_2\rangle =\ & -\frac{1}{4}\,{\rm e}^{-5\pi{\rm i}/4}[(|g_1g_2g_3\rangle - |e_1e_2g_3\rangle - |e_1g_2e_3\rangle - |g_1e_2e_3\rangle)|g_4\rangle \\ & -(|g_1e_2e_3\rangle - |g_1g_2g_3\rangle - |e_1g_2e_3\rangle - |e_1e_2g_3\rangle)|g_4\rangle\end{aligned}$$

$$-(|g_1e_2g_3\rangle - |e_1g_2g_3\rangle - |e_1e_2e_3\rangle - |g_1g_2e_3\rangle)|e_4\rangle$$
$$-(|g_1g_2e_3\rangle - |e_1e_2e_3\rangle - |e_1g_2g_3\rangle - |g_1e_2g_3\rangle)|e_4\rangle], \quad (6)$$

i.e.

$$|\psi_2\rangle = -\frac{1}{2}\,\mathrm{e}^{-5\pi\mathrm{i}/4}(|g_2g_3g_1g_4\rangle + |g_2g_3e_1e_4\rangle - |e_2e_3g_1g_4\rangle + |e_2e_3e_1e_4\rangle). \quad (7)$$

Now we perform the operation $\sigma_{z,2} = |e\rangle_2\langle e| - |g\rangle_2\langle g|$ on ion 2, whereas there is no operation acted on the ions 1, 3, and 4, thus the state of the system evolves into

$$|\psi\rangle = \frac{1}{2}(|g_2g_3g_1g_4\rangle + |g_2g_3e_1e_4\rangle + |e_2e_3g_1g_4\rangle - |e_2e_3e_1e_4\rangle), \quad (8)$$

where a common factor $\mathrm{e}^{-5\pi\mathrm{i}/4}$ is discarded. This is a four-atom entangled cluster state.

Here we will discuss the experimental feasibility of the proposed scheme. For the Rydberg atoms, the radiative time is about $T_\mathrm{r} = 3 \times 10^{-2}$ s and the coupling constant is $g = 2\pi \times 24$ kHz.[21,22] We choose $\delta = 10g$, the required atom–cavity–field interaction time is $T = 2t_1 \approx 2 \times 10^{-4}$ s, much shorter than the spontaneous radiative time. Thus the losses due to the spontaneous emission can be neglected. Meanwhile from Eq. (1) it is noted that the atomic state evolution is independent of the cavity field state, so the effects of the cavity decay and thermal field have been eliminated. So our scheme is realisable.

The main experimental challenge for our scheme is to control three atoms to go through a cavity simultaneously with the same velocity. But in a real experiment there are some errors. While we have not yet found any experimental report of more than one atom going through a cavity simultaneously,[21] we expect more advanced cavity QED techniques to carry out our scheme. Because the two-atom entangled state has also been prepared by the atom–cavity field interaction and has been experimentally realized,[21] for simplification, we assume that atoms 2 and 3 are sent through the cavity simultaneously. Assume that during the generation of the state the atoms 2 and 3 enter the cavity C_1 $0.01t_1$ earlier than the atom 4, and the atoms 2 and 3 enter the cavity C_2 $0.01t_2$ earlier than the atom 1. Another difficulty for the present scheme is that the Rabi frequency Ω has a fluctuation $\Omega + \Delta\Omega$. Assume $\Delta\Omega = 0.01\Omega$. We choose $\lambda t_1 = \lambda t_2 = \lambda t = \pi/4$ and $(\Omega t)_1 = (\Omega t)_2 = \pi$, Then the four atoms (after interaction) are approximately prepared in the state (see the Appendix)

$$|\varphi\rangle \approx -\frac{1}{2}\,\mathrm{e}^{\mathrm{i}(0.02\lambda t)}\,\mathrm{e}^{-5\pi\mathrm{i}/4}\cos^2(0.01\lambda t)\cos^2(0.02\lambda t)\cos^6(\Omega+\Delta\Omega)\Delta t\cos^6((\Omega+\Delta\Omega)(t+\Delta t))(|g_2g_3g_1g_4\rangle + |g_2g_3e_1e_4\rangle - |e_2e_3g_1g_4\rangle + |e_2e_3e_1e_4\rangle). \quad (9)$$

Thus the fidelity of the obtained cluster state is $F = 0.9886$. Therefore we can conclude that the small fluctuation of the Rabi frequency Ω and the small error of the interaction time only affect the fidelity of the resulted state slightly.

We note that the scheme can also be applied to the ion trap system. We consider that N ions are confined in a linear trap. We simultaneously excite the ions by two homogeneous lasers with frequencies $\omega_0 + \nu + \delta$ and $\omega_0 - \nu - \delta$, where ω_0 is the frequency of the electronic transition $|e\rangle \to |g\rangle$ and ν is the frequency of the centre-of-mass mode of the collective motion of the ions. Assuming $\delta \ll \nu$, then we find that the excitation of the stretch modes is far off-resonant and can be discarded. We consider the resolved sideband regime, where the vibrational frequency ν is much larger than other characteristic frequencies. In the Lamb–Dicke regime, i.e., the spatial extension of the atomic wave function is much smaller than the wavelength of the lasers, the Hamiltonian in the interaction picture is[20]

$$\hat{H} = \mathrm{i}\Omega\eta\,\mathrm{e}^{-\mathrm{i}\phi}\sum_{j=1}^{N}(\hat{S}_j^+ + \hat{S}_j^-)(\hat{a}^+\,\mathrm{e}^{-\mathrm{i}\delta t} + \hat{a}\,\mathrm{e}^{\mathrm{i}\delta t}). \quad (10)$$

Where Ω is the same Rabi frequency, η is the Lamb–Dicke parameter, and $\hat{a}^+(\hat{a})$ denotes the creation (annihilation) operator for the centre-of-mass mode of the collective motion of the ions.

When $\delta \gg \eta\Omega$, there is no energy exchange between the ionic system and the vibrational mode. Assuming $\phi = \pi/2$, we get the effective Hamiltonian[20]

$$H_{\rm eff} = 2\lambda S_x^2. \tag{11}$$

The effective Hamiltonian is independent of the vibrational quantum number. Thus the vibrational state of the ions can be a thermal state in principle. In addition, the effective Hamiltonian has similar form as Eq. (1), with $\lambda = 2\eta^2\Omega^2/\delta$. Thus we can generate the entangled cluster states of four trapped ions by using the procedure similar to that for cavity QED.

If three ions initially in the state $|x_1x_2x_3\rangle$ are simultaneously illuminated by two classical homogeneous lasers of frequencies $\omega_0+\nu+\delta$ and $\omega_0-\nu-\delta$, then the state of three ions will evolve into

$$\begin{aligned}|x_1x_2x_3\rangle \longrightarrow\ & {\rm e}^{-5\lambda t{\rm i}/2}\Big[\cos(2\lambda t)|x_1x_2x_3\rangle \\ & +\frac{\rm i}{2}\sin(2\lambda t)(|x_1x_2x_3\rangle - |\bar{x}_1\bar{x}_2x_3\rangle \\ & -|\bar{x}_1x_2\bar{x}_3\rangle - |x_1\bar{x}_2\bar{x}_3\rangle)\Big],\end{aligned} \tag{12}$$

where $x \in \{g, e\}$ and $\bar{x}$ is the counterpart of the binary number x. With the choice of $\lambda t = \pi/4$, we obtain the three-ion entangled state

$$\begin{aligned}|x_1x_2x_3\rangle \longrightarrow\ & \frac{\rm i}{2}\,{\rm e}^{-5\pi{\rm i}/8}(|x_1x_2x_3\rangle - |\bar{x}_1\bar{x}_2x_3\rangle \\ & -|\bar{x}_1x_2\bar{x}_3\rangle - |x_1\bar{x}_2\bar{x}_3\rangle).\end{aligned} \tag{13}$$

The scheme for preparing four-ion cluster state is similar to the one in cavity QED. The four-ion cluster state has the same form as Eq. (8). The main factor that decreases the quality (fidelity) of the generated four-ion cluster state may be the intensity fluctuation of the laser fields.[25] Now we estimate such an error. Suppose that the fluctuation of the Rabi frequency of the laser fields is $\Delta\Omega = 0.01\Omega$ and $\Delta\lambda = 0.0201\lambda$. Then the four ions (after interaction) are approximately prepared in the state

$$\begin{aligned}|\varphi\rangle \approx\ & -\frac{1}{2}\,{\rm e}^{{\rm i}2\Delta\lambda t}\,{\rm e}^{-5\pi{\rm i}/4}\cos^2 2\Delta\lambda t(|g_2g_3g_1g_4\rangle \\ & +|g_2g_3e_1e_4\rangle - |e_2e_3g_1g_4\rangle + |e_2e_3e_1e_4\rangle).\end{aligned} \tag{14}$$

Then the fidelity is $F = 0.9990$. Therefore the small fluctuation of the Rabi frequency only affects the fidelity of the resulted state slightly.

In conclusion, we have proposed a simple scheme to prepare a four-atom entangled cluster state in a thermal cavity. Compared with previous schemes, our scheme has two distinct advantages. First, the success probability is 1 which the optical system can never reach. Second, the cavity field is only virtually excited and the photon-number-dependent part in the effective Hamiltonian is canceled with the assistance of a strong classical driving field. Thus our scheme is insensitive to cavity decay and the thermal field. For the trapped-ion system, our scheme is insensitive to the thermal motion. Our scheme is reachable by the near future cavity QED techniques and the present ion trap techniques.

Appendix

We estimate the fidelity in the experiment. Firstly, we assume that the whole time for atoms 2, 3, and 4 passing through the cavity C_1 is t_1, and atoms 2 and 3 are earlier than atom 4 to enter the cavity C_1 by the difference Δt_1. Secondly, we assume that the whole time for atoms 2, 3, and 1 passing through the cavity C_2 is t_2, and atoms 2 and 3 are earlier than atom 1 to enter the cavity C_2 by the difference Δt_2. We assume that the Rabi frequency Ω has a fluctuation $\Omega + \Delta\Omega$. According to Eq. (4) in the text, the whole system's evolution is described as follows:

$$U_6U_5U_4U_3U_2U_1|\psi(0)\rangle \tag{A1}$$

with

$$\begin{cases}|\psi(0)\rangle = |g_1g_2g_3g_4\rangle, \\ U_1 = {\rm e}^{-{\rm i}2[(\Omega+\Delta\Omega)S_{x23}+\lambda S_{x23}^2])\Delta t_1}, \\ U_2 = {\rm e}^{-{\rm i}2[(\Omega+\Delta\Omega)S_{x234}+\lambda S_{x234}^2)(t_1-\Delta t_1]}, \\ U_3 = {\rm e}^{-{\rm i}2[(\Omega+\Delta\Omega)S_{x4}+\lambda S_{x4}^2]\Delta t_1}, \\ U_4 = {\rm e}^{-{\rm i}2[(\Omega+\Delta\Omega)S_{x23}+\lambda S_{x23}^2]\Delta t_2}, \\ U_5 = {\rm e}^{-{\rm i}2[(\Omega+\Delta\Omega)S_{x231}+\lambda S_{x231}^2](t_2-\Delta t_2)}, \\ U_6 = {\rm e}^{-{\rm i}2[(\Omega+\Delta\Omega)S_{x1}+\lambda S_{x1}^2]\Delta t_2},\end{cases} \tag{A2}$$

where $S_{x1} = (S_1^+ + S_1^-)/2$, $S_{x23} = \sum_{j=2}^3(S_j^+ + S_j^-)/2$, $S_{x234} = \sum_{j=2}^4(S_j^+ + S_j^-)/2$, $S_{x231} = \sum_{j=1}^3(S_j^+ + S_j^-)/2$ and $S_{x4} = (S_4^+ + S_4^-)/2$ $S_j^+ = |e\rangle_j\langle g|$, $S_j^- = |g\rangle_j\langle e|$, with $|e\rangle_j$ and $|g\rangle_j$ being the excited and ground states of the jth atom. Using

$$\begin{aligned}|x\rangle \longrightarrow\ & {\rm e}^{-{\rm i}\lambda t/2}(\cos(\Omega t)|x\rangle - {\rm i}\sin(\Omega t)|\bar{x}\rangle, \\ |x_1x_2\rangle \longrightarrow\ & {\rm e}^{-{\rm i}\lambda t}[\cos\lambda t(\cos(\Omega t)|x_1\rangle \\ & -{\rm i}\sin(\Omega t)|\bar{x}_1\rangle)(\cos(\Omega t)|x_2\rangle \\ & -{\rm i}\sin(\Omega t)|\bar{x}_2\rangle)\end{aligned}$$

$$
\begin{aligned}
&- \mathrm{i}\sin\lambda t(\cos(\Omega t)|\bar{x}_1\rangle \\
&- \mathrm{i}\sin(\Omega t)|x_1\rangle)(\cos(\Omega t)|\bar{x}_2\rangle \\
&- \mathrm{i}\sin(\Omega t)|x_2\rangle)], \qquad \text{(A3)}
\end{aligned}
$$

and Eq. (3) and choosing $\lambda t_1 = \lambda t_2 = \pi/4$ and $(\Omega t)_1 = (\Omega t)_2 = \pi$, we can obtain the derivation of final inexact (noise) state $|\varphi\rangle$ and the fidelity $F = 0.9886$.

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