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Generation of atomic Greenberger–Horne–Zeilinger states and cluster states through cavity-assisted interaction*

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This paper proposes a scalable scheme to generate n-atom GHZ states and cluster states by using the basic building block, i.e., a weak coherent optical pulse $|\alpha\rangle$ being reflected successively from a single-atom cavity. In the schemes, coherent state of light is used instead of single photon source, homodyne measurement on coherent light is done instead of single photon detection, and no need for individually addressing keeps the schemes easy to implement from the experimental point of view. The successful probabilities of our protocols approach unity in the ideal case.

Keywords: GHZ state, cluster states, cavity QED
PACC: 0367, 4250

1. Introduction

Entanglement is a characteristic feature of quantum states and has important applications in quantum science and technology, such as quantum cryptography,[1] quantum dense coding,[2] and quantum teleportation.[3] The GHZ state is one of the important classes of multipartite entanglement state and can be employed as a quantum channel for quantum key distribution[4] and quantum secret sharing.[5] The cluster state,[6] another multipartite entanglement state, has been shown to constitute a universal resource for quantum computation via local, single-qubit projective measurements and feedforward of their outcomes.[7] Hence, the generation of Greenberger–Horne–Zeilinger (GHZ) state and cluster state is current topic in the theory and the laboratory.[8−21] So far, there have been a lot of theoretical protocols for generating GHZ state and cluster state with optical systems, superconductor, trapped ions, atomic ensembles, cavity QED, and so on.[22−24] Since the cavity QED system is an alternative promising candidate for quantum-information processing, Lin *et al* proposed a scheme to prepare multiple-atom and multiple-photon GHZ states based on the input-output relation of the cavity.[25] Recently, Cho *et al* proposed a novel scheme for robust generation of atomic cluster states via the cavity input-output process and the single photon polarization measurement.[14] Among these schemes, most of them use single-photon sources and/or single-photon detectors. Although there are great progresses in the study on these single-photon devices, reliable and efficient single photon sources and detectors are further issues for single photon approaches.[26−28] Here, we propose a scalable scheme to prepare n-atom GHZ states and cluster states using weak coherent optical pulse and homodyne measurements, where homodyne measurements on coherent light fields can be made much more efficient than single photon detection. The successful probabilities of our protocols approach unity in the ideal case. In addition, the atoms have no probability of being populated in the excited states and no need of real transition of atomic internal states during the whole process, thus the atomic spontaneous emission is suppressed. No need for individually addressing keeps the schemes easy to implement from the experimental point of view.

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2. The fundamental model

First, let us briefly introduce a basic building block of this scheme. As illustrated in Fig.1, we consider an atom with three relevant levels trapped inside a one-sided optical cavity, where $|0\rangle$ and $|1\rangle$ are two stable ground states of atom, and $|e\rangle$ is a low excited state. The qubit is encoded in the two ground levels $|0\rangle$ and $|1\rangle$. The atomic transition $|1\rangle \rightarrow |e\rangle$ is resonantly coupled to a cavity mode $a_{\rm c}$, which is resonantly driven by an input optical pulse prepared in a weak coherent state $|\alpha\rangle$.

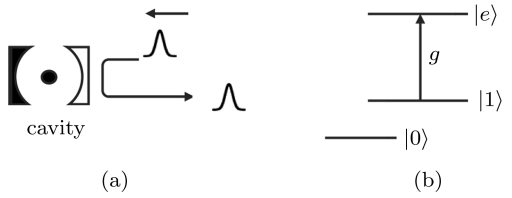


Fig.1. (a) Schematic setup for generating the entanglement $\frac{1}{\sqrt{2}}(|0\rangle|\alpha\rangle + |1\rangle|-\alpha\rangle)$ by reflecting a coherent optical pulse from a single-atom cavity. (b) The relevant level structure of the atom trapped in the cavity.

In the limit with $T \gg 1/\kappa$ (here T is the pulse duration and κ is the cavity decay rate), if the atom is in the state $|0\rangle$, the input coherent light $|\alpha\rangle$ is resonantly reflected by the bare cavity mode and it subsequently achieves a flipped phase $\mathrm{e}^{\mathrm{i}\pi}$, i.e. the state $|\alpha\rangle$ will become the state $|-\alpha\rangle$ after the reflection. If the atom is in the state $|1\rangle$, the effective frequency of the dressed cavity mode will be shifted due to the atom–cavity coupling, which is described by the interaction Hamiltonian $H = g(|e\rangle\langle 1|\, a_{\rm c} + |1\rangle\langle e|\, a_{\rm c}^{\dagger})$, where g denotes the coupling constant between the cavity mode and corresponding atomic transition $|1\rangle \rightarrow |e\rangle$, $a_{\rm c}$ and $a_{\rm c}^{+}$ are the annihilation and creation operators for the cavity mode respectively. If the coupling rate satisfies $g \gg (1/T,\ \kappa,\ \gamma)$, where γ is the rate of spontaneous decay of the excited state $|e\rangle$, the frequency shift will have a magnitude comparable with g so that the incident coherent optical pulse will be reflected by an off-resonant cavity. Hence, both the shape and global phase for the reflected pulse will remain unchanged. So the pulse will remain in the same state $|\alpha\rangle$ after the reflection, when the amplitude α of the input pulse is not too large.[29,30] We simply prepare the trapped atom in a superposition state $\frac{1}{\sqrt{2}}(|0\rangle+|1\rangle)$. A coherent pulse $|\alpha\rangle$ is then reflected from the single-atom cavity. Following the above analysis, we find that the final atom–photon state will become an entangled state, i.e.

$$\begin{aligned} |\Psi\rangle_1 &= R_i \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)_i \otimes |\alpha\rangle \\ &= \frac{1}{\sqrt{2}}(|0\rangle_i |-\alpha\rangle + |1\rangle_i |\alpha\rangle), \end{aligned} \tag{1}$$

where R_i denotes the effect of a weak coherent optical pulses $|\alpha\rangle$ being reflected by the i-th single-atom cavity.

3. The generation of n-atom GHZ state

Now we describe in detail how to generate an n-atom GHZ state. We first prepare a two-atom GHZ state. As plotted in Fig.2, both atoms 1 and 2 are initially prepared in a superposition state $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ and the input optical pulse is prepared in a weak coherent state $|\alpha\rangle$, where the weak coherent state $|\alpha\rangle$ is injected from the left. After the weak coherent state $|\alpha\rangle$ in turn interacts with the atoms 1 and 2, an operation R_2R_1 is applied on the two atoms and the injected coherent optical pulse $|\alpha\rangle$, and the final atom-photon state will become an entangled state

$$\begin{aligned} |\Psi\rangle_2 &= R_2R_1 \prod_{i=1}^{2} \frac{1}{\sqrt{2}}(|0\rangle_i + |1\rangle_i) \otimes |\alpha\rangle \\ &= \frac{1}{2}(|00\rangle + |11\rangle)_{12} |\alpha\rangle \\ &\quad + \frac{1}{2}(|01\rangle + |10\rangle)_{12} |-\alpha\rangle . \end{aligned} \tag{2}$$

Then a homodyne measurement $|X\rangle\langle X|$[31] is performed on the reflected coherent pulse, with the measurement result X to distinguish the beam $|\alpha\rangle$ from $|-\alpha\rangle$. When the measurement result is $|\alpha\rangle$ (or $|-\alpha\rangle$), the state of the two atoms will collapse to $|\Psi\rangle_{20} = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$ (or $|\Psi\rangle_{21} = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$), every which can be occurred with the same determinate probability $\frac{1}{2}$. Thus the total success probability of preparing a two-atom GHZ state is unity. In a word, the proclamation of the homodyne measurement result gives the parity of the two atoms and projects them into a known two-qubit entangled state.

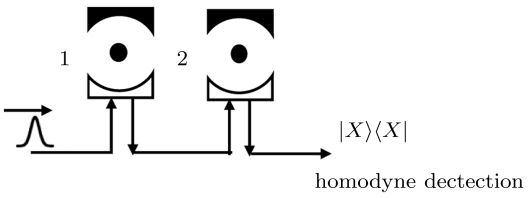


Fig.2. Schematic setup for preparing two-qubit GHZ state and cluster state between atom 1 and atom 2. $|X\rangle\langle X|$ represents the homodyne detection.

Secondly, we prepare a three-atom GHZ state. Assume that the state of atoms 1 and 2 has been prepared in $|\Psi\rangle_{20} = \frac{1}{\sqrt{2}}(|00\rangle+|11\rangle)$ and the state of atom 3 is initially in the superposition state $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$. If the operation R_3R_2 is performed on atoms 2, 3, and the injected coherent optical pulse $|\alpha\rangle$, one has

$$\begin{aligned}|\Psi\rangle_3 &= R_3R_2\frac{1}{\sqrt{2}}(|00\rangle_{12} + |11\rangle_{12}) \\ &\otimes\frac{1}{\sqrt{2}}(|0\rangle_3 + |1\rangle_3)\otimes|\alpha\rangle \\ &= \frac{1}{2}(|000\rangle + |111\rangle)|\alpha\rangle \\ &+\frac{1}{2}(|001\rangle + |110\rangle)|-\alpha\rangle\,. \end{aligned} \quad (3)$$

After a homodyne measurement is performed on the reflected coherent pulse, the outcome of the measurement will project the state of atoms 1, 2 and 3 into a known three-qubit GHZ state. When the result of the homodyne measurement is $|\alpha\rangle$ (or $|-\alpha\rangle$), the state of the three atoms will collapse to $|\Psi\rangle_{30} = \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$ (or $|\Psi\rangle_{31} = \frac{1}{\sqrt{2}}(|001\rangle + |110\rangle)$).

Finally, we show how to prepare an n-atom GHZ state. Similarly, suppose that the state of $(n-1)$ atoms has been prepared in $\frac{1}{\sqrt{2}}(|00\ldots0\rangle_{n-1} + |11\ldots1\rangle_{n-1})$ and the state of atom n is initially in the superposition state $\frac{1}{\sqrt{2}}(|0\rangle_n + |1\rangle_n)$. If the operation R_nR_{n-1} is performed on atoms $(n-1)$, n, and the injected coherent optical pulse $|\alpha\rangle$, one has

$$\begin{aligned}|\Psi\rangle_n &= R_nR_{n-1}\frac{1}{\sqrt{2}}(|00\ldots0\rangle_{n-1} + |11\ldots1\rangle_{n-1}) \\ &\otimes\frac{1}{\sqrt{2}}(|0\rangle_n + |1\rangle\, n)\otimes|\alpha\rangle \\ &= \frac{1}{2}(|00\ldots0\rangle + |11\ldots1\rangle)|\alpha\rangle \\ &+\frac{1}{2}(|0\ldots01\rangle + |1\ldots10\rangle)|-\alpha\rangle\,. \end{aligned} \quad (4)$$

After a homodyne measurement is performed on the output coherent pulse, the result of the measurement will project the state of the n atoms into a known n-qubit GHZ state. When the result of the homodyne measurement is $|\alpha\rangle$ (or $|-\alpha\rangle$), the state of the n atoms will collapse to $|\Psi\rangle_{n0} = \frac{1}{\sqrt{2}}(|00\ldots0\rangle_n + |11\ldots1\rangle_n)$ (or $|\Psi\rangle_{n1} = \frac{1}{\sqrt{2}}(|0\ldots01\rangle_n + |1\ldots10\rangle_n)$), which is the n-atom GHZ state.

4. The preparation of n-atom cluster state

We can prepare an n-atom cluster state by making a small modification on the scheme above. The detailed process is described as follows. We first show how to prepare a two-atom cluster state. Suppose that we have obtained the two-atom GHZ state $|\Psi\rangle_{20} = \frac{1}{\sqrt{2}}(|00\rangle+|11\rangle)$, then a single qubit operation S_+ is applied on atom 2, i.e., $S_+|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$, $S_+|1\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$. The state of the two atoms $|\Psi\rangle_{20}$ will transfer to

$$\begin{aligned}|\Phi\rangle_2 &= \frac{1}{2}(|0\rangle_1(|0\rangle_2 + |1\rangle_2) + |1\rangle_1(|0\rangle_2 - |1\rangle_2)) \\ &= \frac{1}{2}(|0\rangle_1 + |1\rangle_1\boldsymbol{\sigma}_z^{(2)})(|0\rangle_2 + |1\rangle_2), \end{aligned} \quad (5)$$

where $\boldsymbol{\sigma}_z^{(i)} = |0\rangle_i\langle 0| - |1\rangle_i\langle 1|$ is the Pauli matrix. Thus we have generated a two-qubit cluster state in the determinate way.

After obtaining the two–atom cluster state, we then show how to prepare a three–atom cluster state. Assume that the state of atoms 1 and 2 has been prepared as that shown in Eq.(5) and the state of atom 3 is initially in the superposition state $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$. After the weak coherent state $|\alpha\rangle$ in turn interacts with the atoms 2 and 3, an operation R_3R_2 is applied on the two atoms and the coherent optical pulse $|\alpha\rangle$. Thus one has

$$\begin{aligned}|\Phi\rangle_3' &= R_3R_2\frac{1}{2}(|0\rangle_1 + |1\rangle_1\boldsymbol{\sigma}_z^{(2)})(|0\rangle_2 + |1\rangle_2) \\ &\otimes\frac{1}{\sqrt{2}}(|0\rangle_3 + |1\rangle_3)\otimes|\alpha\rangle \\ &= \frac{1}{2^{3/2}}(|0\rangle_1 + |1\rangle_1\boldsymbol{\sigma}_z^{(2)})[(|00\rangle \\ &+|11\rangle)_{23}|\alpha\rangle + (|01\rangle + |10\rangle)_{23}|-\alpha\rangle]. \end{aligned} \quad (6)$$

Then a homodyne measurement is performed on the reflected coherent pulse. When the measurement result is $|\alpha\rangle$ ($|-\alpha\rangle$), a single qubit operation S_+ (S_-) is applied on atom 3, where $S_-|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$,

$S_-|1\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$. Thus, the state of the three atoms will become

$$|\Phi\rangle_3 = \frac{1}{2^{3/2}}(|0\rangle_1 + |1\rangle_1 \boldsymbol{\sigma}_z^{(2)})(|0\rangle_2 + |1\rangle_2 \boldsymbol{\sigma}_z^{(3)})(|0\rangle_3 + |1\rangle_3), \quad (7)$$

which is just the three-qubit cluster state.

One can take a simple add-on strategy to generate the n-atom cluster state. As shown in Fig.3, the line between particles denotes a previous nearest neighbour interaction. Suppose that the state of $(n-1)$ atoms has been prepared in the one-dimensional (1D) cluster state $|\Phi_{n-1}\rangle = \frac{1}{2^{(n-1)/2}} \otimes_{i=1}^{n-2} (|0\rangle_i + \boldsymbol{\sigma}_z^{(i+1)}|1\rangle_i)(|0\rangle_{n-1} + |1\rangle_{n-1})$. The state of atom n is initially in the superposition state $\frac{1}{\sqrt{2}}(|0\rangle_n + |1\rangle_n)$. After the weak coherent state $|\alpha\rangle$ in turn interacts with the atoms $(n-1)$ and n, an operation R_nR_{n-1} is applied on the two atoms and the coherent optical pulse $|\alpha\rangle$. Thus one has

$$\begin{aligned}|\Phi\rangle_n' &= R_nR_{n-1}\frac{1}{2^{(n-1)/2}}(|0\rangle_1 + |1\rangle_1 \boldsymbol{\sigma}_z^{(2)}) \\ &\quad \ldots(|0\rangle_{n-2} + |1\rangle_{n-2}\boldsymbol{\sigma}_z^{(n-1)})(|0\rangle_{n-1} + |1\rangle_{n-1}) \\ &\quad \otimes \frac{1}{\sqrt{2}}(|0\rangle_n + |1\rangle_n) \otimes |\alpha\rangle \\ &= \frac{1}{2^{n/2}}(|0\rangle_1 + |1\rangle_1 \boldsymbol{\sigma}_z^{(2)}) \\ &\quad \ldots(|0\rangle_{n-2} + |1\rangle_{n-2}\boldsymbol{\sigma}_z^{(n-1)}) \\ &\quad \times[(|00\rangle + |11\rangle)_{n-1,n}|\alpha\rangle + (|01\rangle \\ &\quad + |10\rangle)_{n-1,n}|-\alpha\rangle]. \end{aligned} \quad (8)$$

Then a homodyne measurement is performed on the reflected coherent pulse. When the measurement result is $|\alpha\rangle$ ($|-\alpha\rangle$), a single qubit operation S_+ (S_-) is applied on atom n. Thus the state of the n atoms will evolve to

$$|\Phi\rangle_n = \frac{1}{2^{n/2}} \otimes_{i=1}^{n-1} (|0\rangle_i + \boldsymbol{\sigma}_z^{(i+1)}|1\rangle_i)(|0\rangle_n + |1\rangle_n), \quad (9)$$

which is the n-atom cluster state.

Similarly, we can prepare 2D cluster states, as plotted in Fig.4. Suppose that we have prepared 1D n-atom cluster state $|\Phi_n\rangle$ and atom $(n+1)$ in the state $\frac{1}{\sqrt{2}}(|0\rangle_{n+1} + |1\rangle_{n+1})$. An operation $R_{n+1}R_m$ is performed on atoms m and $n+1$, then a single qubit operation S_+ or S_- is applied on atom $n+1$ depending on the homodyne measurement result. Thus one can get the 2D cluster state $|\Phi_{n+1}\rangle$. By taking a simple add-on strategy and repeating the procedures above, one can generate the 2D cluster states of an arbitrary configuration.

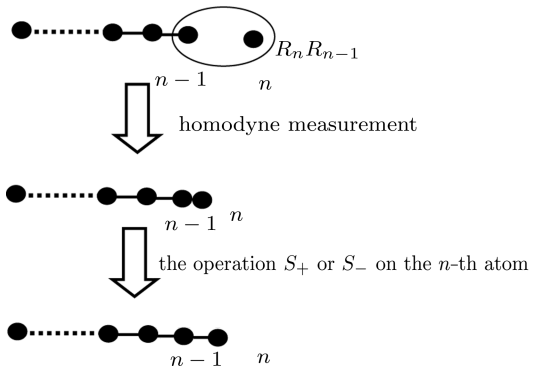


Fig.3. Schematic setup for implementing the one-dimensional (1D) cluster state by taking a simple add-on strategy. The line between particles denotes a previous nearest neighbour interaction. The ellipse denotes that the operation R_nR_{n-1} is applied on the two atoms and the coherent optical pulse $|\alpha\rangle$.

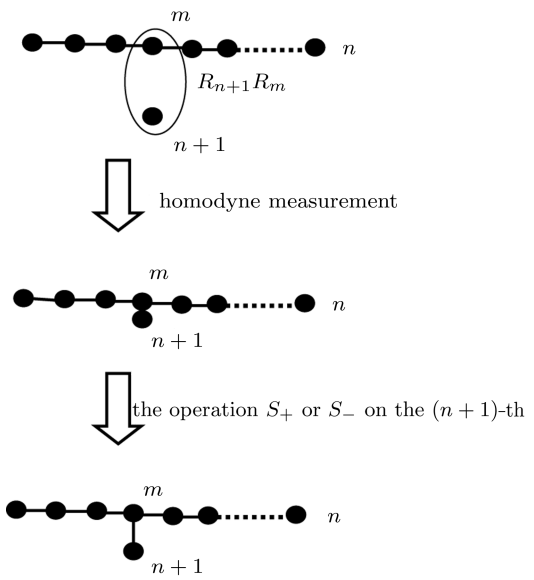


Fig.4. Schematic setup for implementing the two-dimensional (2D) cluster state.

5. Discussion and conclusion

We briefly discuss the feasibilities of preparing the GHZ states and cluster states. In our scheme, two logical states of a qubit are encoded on the two stable low-energy states, which have long lifetime. There are three parts in the total operations, i.e., the basic building block that a weak coherent optical pulses

$|\alpha\rangle$ being reflected from the single-atom cavity to perform R_i, homodyne measurement and single qubit operation S_ξ ($\xi = +, -$). First of all, the basic building block has been discussed and numerically simulated in Ref.[29], which shows that the fidelity increases with the coupling rate g and decreases with the cat amplitude α. Under a reasonable atom-cavity coupling rate $g \approx 10\kappa$ and the coherent state amplitude $\alpha = 2.0$, one can get a comparable high fidelity about 98% with the current technology. Secondly, the distinguishability of the homodyne detection is determined by the distance $d_{\rm HD} = \alpha(1 - \cos\theta)$. In our scheme, there is $\theta = \pi$ corresponding to the phase difference between $|\alpha\rangle$ and $|-\alpha\rangle$. By choosing the coherent state amplitude $\alpha \approx 2.0$, we find that the error probability of the homodyne measurement is $P_{\rm err} \approx 10^{-4}$ for $d_{\rm HD} = 4$.[32] Furthermore, unlike the case of single photon detection, the photon losses only decrease the signal-to-noise ratio but do not lead to a failure in the measurements, since a homodyne detection of the coherent state directly measures the relative phase of the signal state.[30] Finally, because the single operations on the atoms trapped in different cavities can be easily implemented by radio-frequency (RF) pulses or Raman transition, the influence of single qubit operation in our scheme can be neglected. In a review of recent experiments in cavity QED, the trapping and cooling of individual atoms in a regime of strong coupling have been achieved.[33,34] In particular, trapping lifetimes in excess of 1 s have been obtained.[35] The transmission spectrum for an atom trapped and strongly coupled to the field of a high finesse optical resonator has been observed.[34] All of these progresses make our protocols possible to implement experimentally in the near future.

In summary, we propose a scalable scheme to generate n-atom GHZ states and cluster states. The successful probabilities of our protocols approach unity in the ideal case. In addition, the atoms have no probability of being populated in the excited states and real transition of atomic internal states is not required during the whole process, thus the atomic spontaneous emission is suppressed. Homodyne measurement on coherent light fields instead of single photon detection is much more efficient. Single-photon resource and individually addressing are not needed. All of these keep the schemes easy to implement from the experimental point of view.

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