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Scheme for teleportation of an unknown atomic state via a cluster state in cavity QED*

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This paper proposes an experimentally feasible scheme for teleportation of an unknown two-atom entangled state, where a cluster state is used as the quantum channel. This scheme does not need any joint measurement. In addition, the successful probability and fidelity of teleportation can both reach 1.0. The current scheme can be realized within the current experimental technology.

Keywords: quantum teleportation, joint measurement, quantum controlled phase gate, cavity QED
PACC: 0367, 0365, 4250

1. Introduction

Quantum entanglement is one of the most important resources for fundamental studies in quantum information processing, such as quantum computing,[1,2] quantum dense coding,[3] quantum teleportation,[4−6] and so on.

In particular, since teleportation was first proposed by Bennett *et al*[4] and then demonstrated by Bouwmeester *et al*[5] and Boschi *et al*,[6] it has drawn much attention because of its fresh notion and latent applied prospects in quantum calculation and quantum communication.[7−10] In the process of the teleportation, a sender (Alice) sends an unknown quantum state through the quantum channel to a receiver (Bob) with the help of the classical channel. Recently, many different theoretical and experimental schemes for teleportation of an unknown entangled state have been proposed.[11−21] In order to avoid the experimental complexity of teleportation, Zheng[19] proposed a scheme for teleporting an unknown atomic state in cavity QED without the joint measurements, but the probability of success is only 0.25. We also presented two teleportation schemes.[20,21] One is the scheme for teleportation of an unknown atomic state without the joint measurements in cavity QED, it is insensitive to the cavity decay and thermal field, and the successful probability is 1.0. The other one is the scheme for teleportation of an unknown entangled atomic state, where a cluster state is used as the quantum channel. Following our latter scheme, here we propose a physical scheme to realize the teleportation of an unknown entangled atomic state in cavity QED. Also, the current scheme does not need any joint measurement and is insensitive to both the cavity decay and thermal field. Moreover the successful probability and the fidelity of output state can both reach 1.0.

The paper is organized as follows. In Section 2, we present a scheme for teleporting a special two-atom entangled state via a cluster state. In Section 3, we propose a scheme for teleporting an arbitrary and unknown two-atom entangled state via a cluster state. Finally, in Section 4, we discuss the experimental feasibility of our scheme.

2. Teleportation of a special two-atom entangled state

Suppose the unknown entangled state to be teleported has the following form:

$$|\Psi\rangle_{12} = a|gg\rangle_{12} + d|ee\rangle_{12}, \tag{1}$$

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where a and d are the unknown parameters, $|a|^2 + |d|^2 = 1$. This is an unknown entangled state for the sender (Alice). We will teleport the entangled state by using a four-atom cluster state as the quantum channel. The quantum channel is

$$|\Psi\rangle_{3456} = \frac{1}{2}(|gggg\rangle + |ggee\rangle + |eegg\rangle - |eeee\rangle)_{3456}, \quad (2)$$

the atoms 3 and 6 belong to the sender (Alice), and the other two atoms 4 and 5 belong to the receiver (Bob). All the atoms are three-level atoms, $|g\rangle$ and $|e\rangle$ are the ground state and the excited state of atoms respectively, and the third level $|i\rangle$ is not affected in this model, the subscripts denote the ordinal number of atoms.

Initially, the total state of the system can be expressed as

$$\begin{aligned}|\Psi\rangle &= |\Psi\rangle_{12} \otimes |\Psi\rangle_{3456} = \frac{1}{2}(a|gg\rangle + d|ee\rangle)_{12} \\ &\otimes(|gggg\rangle + |ggee\rangle + |eegg\rangle - |eeee\rangle)_{3456}, \quad (3)\end{aligned}$$

which can be rewritten as

$$\begin{aligned}|\Psi\rangle = -\frac{1}{4}[&(\pm^1 \pm^2 a|gg\rangle_{45} + d|ee\rangle_{45})|\Phi^{\pm}\rangle_{13}|\Phi^{\pm}\rangle_{26} \\ &+(\pm^1 \mathrm{i}a|ge\rangle_{45} \pm^2 \mathrm{i}d|eg\rangle_{45})|\Phi^{\pm}\rangle_{13}|\Psi^{\pm}\rangle_{26} \\ &+(\pm^2 \mathrm{i}a|eg\rangle_{45} \pm^1 \mathrm{i}d|ge\rangle_{45})|\Psi^{\pm}\rangle_{13}|\Phi^{\pm}\rangle_{26} \\ &+(a|ee\rangle_{45} \pm^1 \pm^2 d|gg\rangle_{45})|\Psi^{\pm}\rangle_{13}|\Psi^{\pm}\rangle_{26}], \quad (4)\end{aligned}$$

where $|\Phi^{\pm}\rangle_{ij}$ and $|\Psi^{\pm}\rangle_{ij}$ are the Bell states of the atom pair (i, j), and the Bell states have the forms: $|\Phi^{\pm}\rangle_{ij} = \frac{1}{\sqrt{2}}(|ee\rangle_{ij} \pm \mathrm{i}|gg\rangle_{ij})$, and $|\Psi^{\pm}\rangle_{ij} = \frac{1}{\sqrt{2}}(|ge\rangle_{ij} \pm \mathrm{i}|eg\rangle_{ij})$. The superscripts 1 and 2 in Eq.(4) denote the Bell states composed of the atom pairs (1, 3) and (2, 6), respectively.

From Eq.(4) we can see that, if Alice can easily realize joint Bell-state measurements on atom pairs (1, 3) and (2, 6), then after being informed the measurement results, Bob can restore the original entangled state by corresponding unitary transformation. But the experimental realization of joint Bell-state measurements is complex, so here Alice adopts separate atomic measurements scheme to realize the Bell-state measurements by utilizing optical cavity.

Alice makes two identical ladder-type three-level atoms interact with a single-mode cavity field simultaneously, at the same time the atoms are driven by a classical field. We assume that the transition frequency $|e\rangle \Leftrightarrow |i\rangle$ is highly detuned from the cavity model frequency, so that the total process is not affected by the interaction between cavity model and atoms. While the case of $\omega_0 = \omega$ and $\Omega \gg \delta \gg \varepsilon$ (Ω is the Rabi frequency of the classical field, δ is the detuning between atomic $|e\rangle \Leftrightarrow |g\rangle$ transition frequency ω_0 and cavity frequency ω_a, ω is the frequency of the driving field, ε is the coupling constant between atom and cavity field), there is no energy exchange between the atomic system and the cavity, thus the scheme is insensitive to both the cavity decay and the thermal field. Then in the rotating-wave approximation, the effective interaction Hamiltonian between the single-mode cavity and the atoms is[22]

$$\begin{aligned}H_{\mathrm{e}} = \frac{\chi}{2}\Bigg[&\sum_{j=1}^{2}(|e\rangle_{jj}\langle e| + |g\rangle_{jj}\langle g|) \\ &+ \sum_{i\neq j.i,j=1}^{2}(S_i^+ S_j^- + S_i^+ S_j^+ + \mathrm{H.c.})\Bigg], \quad (5)\end{aligned}$$

where $\chi = \varepsilon^2/2\delta$, $S_j^+ = |e\rangle_{jj}\langle g|$, and $S_j^- = |g\rangle_{jj}\langle e|$.

Then the evolution operator of the system is $U(t) = \mathrm{e}^{-\mathrm{i}H_0 t}\mathrm{e}^{-\mathrm{i}H_{\mathrm{e}} t}$, where $H_0 = \Omega\sum_{j=1,2}(S_j^+ + S_j^-)$.

In order to get the direct product state of atoms, Alice sends the atom pairs (1, 3) and (2, 6) through the single-mode cavity respectively. At the same time, the atom pairs are driven by the classical field. By adjusting the interaction time $\chi t = \pi/4$ and modulating the driving field $\Omega t = \pi$, the atom pair (i, j) will have the following evolutions:

$$\begin{aligned}|gg\rangle_{ij} &\longrightarrow \frac{1}{\sqrt{2}}(|gg\rangle_{ij} - \mathrm{i}|ee\rangle_{ij}), \\ |ge\rangle_{ij} &\longrightarrow \frac{1}{\sqrt{2}}(|ge\rangle_{ij} - \mathrm{i}|eg\rangle_{ij}), \\ |eg\rangle_{ij} &\longrightarrow \frac{1}{\sqrt{2}}(|eg\rangle_{ij} - \mathrm{i}|ge\rangle_{ij}), \\ |ee\rangle_{ij} &\longrightarrow \frac{1}{\sqrt{2}}(|ee\rangle_{ij} - \mathrm{i}|gg\rangle_{ij}). \quad (6)\end{aligned}$$

Thus the Bell states can get the following evolutions:

$$\begin{aligned}|\Phi^+\rangle_{ij} &= \frac{1}{\sqrt{2}}(|ee\rangle_{ij} + \mathrm{i}|gg\rangle_{ij}) \longrightarrow |ee\rangle_{ij}, \\ |\Phi^-\rangle_{ij} &= \frac{1}{\sqrt{2}}(|ee\rangle_{ij} - \mathrm{i}|gg\rangle_{ij}) \longrightarrow -\mathrm{i}|gg\rangle_{ij}, \\ |\Psi^+\rangle_{ij} &= \frac{1}{\sqrt{2}}(|ge\rangle_{ij} + \mathrm{i}|eg\rangle_{ij}) \longrightarrow |ge\rangle_{ij}, \\ |\Psi^-\rangle_{ij} &= \frac{1}{\sqrt{2}}(|ge\rangle_{ij} - \mathrm{i}|eg\rangle_{ij}) \longrightarrow -\mathrm{i}|eg\rangle_{ij}, \quad (7)\end{aligned}$$

where the atom pair (i, j) is the atom pair (1, 3) or (2, 6). It is clear that, according to the Eq.(7), Alice can realize the goal of Bell-state measurements with unit probability of success by separate measurements on her atoms. Thus, after knowing Alice's separate measurement results on atoms 1, 2, 3 and 6, Bob will

be able to reconstruct the original state by applying some appropriate unitary operations.

Without loss of generality, if the measurement results of atoms 1, 3, and 2, 6 are $|ee\rangle_{13}$ and $|gg\rangle_{26}$ respectively, then the atom pair (4, 5) is projected into the state: $a|gg\rangle_{45} - d|ee\rangle_{45}$ (according to Eq.(4) and Eq.(7)). Thus if Bob performs $U_{45} = I_4 \otimes Z_5$ or $U_{45} = Z_4 \otimes I_5$ on the atom pair (4, 5), then there will be an evolution:

$$a|gg\rangle_{45} - d|ee\rangle_{45} \longrightarrow a|gg\rangle_{45} + d|ee\rangle_{45}, \qquad (8)$$

where we have discarded the global phase factor, I and Z are the identity operator and the Pauli operator σ_z respectively, all the subscripts denote the ordinal number of atoms. And the state showed in Eq.(8) is the desired state.

Thus, from the above description we can see that, according to Alice's measurement results, Bob can complete the teleportation procedure successfully by performing relevant unitary transformation on his atom pair. And by calculation we know that the total successful probability $P_{\rm total} = \left(\frac{1}{4}\right)^2 \times 16 = 1$, and the fidelity of the output state is 1.0.

3. Teleportation of an arbitrary and unknown two-atom entangled state

In this section, we assume that the state to be teleported may be expressed as

$$|\Psi\rangle_{12} = a|gg\rangle_{12} + b|ge\rangle_{12} + c|eg\rangle_{12} + d|ee\rangle_{12}, \qquad (9)$$

where a, b, c and d are unknown parameters, and $|a|^2 + |b|^2 + |c|^2 + |d|^2 = 1$. This is an unknown entangled state for the sender (Alice). We will teleport the entangled state by using a four-atom cluster state as the quantum channel. The quantum channel has the same form as that described in Eq.(2). Similarly, the atoms 3 and 6 belong to the sender (Alice), and the other two atoms 4 and 5 belong to the receiver (Bob). All the atoms are three-level atoms, $|g\rangle$ and $|e\rangle$ are the ground state and the excited state of atoms respectively, and all the subscripts denote the ordinal number of atoms.

Initially, the total state of the system can be expressed as

$$\begin{aligned}|\Psi\rangle = |\Psi\rangle_{12} \otimes |\Psi\rangle_{3456} = \frac{1}{2}(a|gg\rangle_{12} + b|ge\rangle_{12} \\ +c|eg\rangle_{12} + d|ee\rangle_{12}) \otimes (|gggg\rangle_{3456} \\ +|ggee\rangle_{3456} + |eegg\rangle_{3456} - |eeee\rangle_{3456}),\end{aligned} \qquad (10)$$

which can be rewritten as

$$\begin{aligned}|\Psi\rangle = -\frac{1}{4}\Big[&(\pm^1 \pm^2 a|gg\rangle_{45} \pm^1 {\rm i}b|ge\rangle_{45} \pm^2 {\rm i}c|eg\rangle_{45} \\ &+d|ee\rangle_{45})|\Phi^{\pm}\rangle_{13}|\Phi^{\pm}\rangle_{26} \\ &+(\pm^1{\rm i}a|ge\rangle_{45} \pm^1 \pm^2 b|gg\rangle_{45} \\ &+c|ee\rangle_{45} \pm^2 {\rm i}d|eg\rangle_{45})|\Phi^{\pm}\rangle_{13}|\Psi^{\pm}\rangle_{26} \\ &+(\pm^2{\rm i}a|eg\rangle_{45} + b|ee\rangle_{45} \pm^1 \pm^2 c|gg\rangle_{45} \\ &\pm^1{\rm i}d|ge\rangle_{45})|\Psi^{\pm}\rangle_{13}|\Phi^{\pm}\rangle_{26} \\ &+(a|ee\rangle_{45} \pm^2 {\rm i}b|eg\rangle_{45} \pm^1 {\rm i}c|ge\rangle_{45} \\ &\pm^1 \pm^2 d|gg\rangle_{45})|\Psi^{\pm}\rangle_{13}|\Psi^{\pm}\rangle_{26}\Big],\end{aligned} \qquad (11)$$

similarly, where $|\Phi^{\pm}\rangle_{ij}$ and $|\Psi^{\pm}\rangle_{ij}$ are the Bell states of the atom pair (i, j) described above, the superscripts 1 and 2 denote the Bell states composed of the atom pairs (1, 3) and (2, 6), respectively. And the experimental realization of joint Bell-state measurement is complex, so here Alice adopts the same method of separate atomic measurements, which is discussed in Section 2, to distinguish the Bell states.

To complete the teleportation, Bob should carry out a quantum controlled phase gate operation on the atoms 4 and 5 at the beginning, in which the atom 4 acts as the control qubit and the atom 5 acts as the controlled qubit.

Here we consider another model of the atoms-cavity field interaction in cavity QED. We assume that two identical ladder-type three-level atoms interact with a single-mode cavity simultaneously. The quantum information is stored in the states $|e\rangle$ and $|g\rangle$. The transition frequency $|e\rangle \Leftrightarrow |i\rangle$ is highly detuned from the cavity model frequency, so that the total process is not affected by the interaction between cavity model and atoms. In the case of $\delta \gg \varepsilon$ (δ and ε have the same meaning as that in Section 2), there is no energy exchange between the cavity and the atomic system, thus the process is insensitive to both the cavity decay and the thermal field. So the effective Hamiltonian of system is[23]

$$\begin{aligned}H_{\rm e} = \lambda[&\sum_{j=1,2}(|e\rangle_{jj}\langle e|aa^+ - |g\rangle_{jj}\langle g|a^+a) \\ &+(S_1^+S_2^- + S_1^-S_2^+)],\end{aligned} \qquad (12)$$

where $\lambda = \varepsilon^2/\delta, S_j^+ = |e\rangle_{jj}\langle g|, S_j^- = |g\rangle_{jj}\langle e|$, the subscripts denote the ordinal number of atoms, a and a^+ are the annihilation operator and creation operator of the cavity model respectively. If we assume that the

cavity mode is in the vacuum state $|0\rangle_v$ initially, the effective Hamiltonian will be reduced to

$$H_{\rm e}^{'} = \lambda \left[\sum_{j=1,2} |e\rangle_{jj}\langle e| + (S_1^+ S_2^- + S_1^- S_2^+) \right]. \quad (13)$$

Bob first makes atom 5 cross a proper classical field, so that atom 5 has the transition: $|e\rangle_5 \longrightarrow |i\rangle_5$. Then he sends the two identical three-level atoms 4 and 5 into a single-model cavity simultaneously, so that they interact with the cavity. According to the effective Hamiltonian in Eq.(13), atom pair (4, 5) will have the following evolution:

$$\begin{aligned} |eg\rangle_{45} &\rightarrow {\rm e}^{-{\rm i}\lambda t}(\cos\lambda t|eg\rangle_{45} - {\rm i}\sin\lambda t|ge\rangle_{45}), \\ |gg\rangle_{45} &\rightarrow |gg\rangle_{45}, |gi\rangle_{45} \longrightarrow |gi\rangle_{45}, \\ |ei\rangle_{45} &\rightarrow {\rm e}^{-{\rm i}\lambda t}|ei\rangle_{45}. \end{aligned} \quad (14)$$

After adjusting the interaction time to make $\lambda t = \pi$, Bob will get

$$\begin{aligned} |gg\rangle_{45} &\longrightarrow |gg\rangle_{45}, |gi\rangle_{45} \longrightarrow |gi\rangle_{45}, \\ |ei\rangle_{45} &\longrightarrow -|ei\rangle_{45}, |eg\rangle_{45} \longrightarrow |eg\rangle_{45}. \end{aligned} \quad (15)$$

And then Bob makes atom 5 cross a proper classical field again, so that atom 5 undergoes the transition $|i\rangle_5 \longrightarrow |e\rangle_5$.

In this way, atoms 4 and 5 have the transformation:

$$\begin{aligned} |gg\rangle_{45} &\longrightarrow |gg\rangle_{45}, |ge\rangle_{45} \longrightarrow |ge\rangle_{45}, \\ |eg\rangle_{45} &\longrightarrow |eg\rangle_{45}, |ee\rangle_{45} \longrightarrow -|ee\rangle_{45}, \end{aligned} \quad (16)$$

here, the transition corresponds to the quantum controlled phase gate operation, in which if and only if atom 4 is in the state $|e\rangle$ atom 5 is performed an operation of Pauli operator σ_z.

Thus Eq.(11) will become

$$\begin{aligned} |\Psi\rangle = -\frac{1}{4}\Big[& (\pm^1 \pm^2 a|gg\rangle_{45} \pm^1 {\rm i}b|ge\rangle_{45} \pm^2 {\rm i}c|eg\rangle_{45} \\ & -d|ee\rangle_{45})|\Phi^{\pm}\rangle_{13}|\Phi^{\pm}\rangle_{26} \\ & +(\pm^1 {\rm i}a|ge\rangle_{45} \pm^1 \pm^2 b|gg\rangle_{45} \\ & -c|ee\rangle_{45} \pm^2 {\rm i}d|eg\rangle_{45})|\Phi^{\pm}\rangle_{13}|\Psi^{\pm}\rangle_{26} \\ & +(\pm^2 {\rm i}a|eg\rangle_{45} - b|ee\rangle_{45} \pm^1 \pm^2 c|gg\rangle_{45} \\ & \pm^1 {\rm i}d|ge\rangle_{45})|\Psi^{\pm}\rangle_{13}|\Phi^{\pm}\rangle_{26} \\ & +(-a|ee\rangle_{45} \pm^2 {\rm i}b|eg\rangle_{45} \pm^1 {\rm i}c|ge\rangle_{45} \\ & \pm^1 \pm^2 d|gg\rangle_{45})|\Psi^{\pm}\rangle_{13}|\Psi^{\pm}\rangle_{26}\Big]. \end{aligned} \quad (17)$$

This operation of the quantum controlled phase gate can be performed before Alice informs Bob of her measurement results. And after knowing the classical information of four qubits coming from Alice, Bob can perform relevant unitary transformation to achieve the teleportation.

Without loss of generality, if the measurement results of atoms 1, 3, and 2, 6 are $|ee\rangle_{13}$ and $|ee\rangle_{26}$ respectively, then atoms 4 and 5 are projected into the state: $a|gg\rangle_{45} + {\rm i}b|ge\rangle_{45} + {\rm i}c|eg\rangle_{45} - d|ee\rangle_{45}$ (according to Eq.(7) and Eq.(17)). Thus if Bob performs a single-qubit local operation $U = S_4 \otimes S_5$ on atoms 4 and 5, where $S = \begin{pmatrix} 1 & 0 \\ 0 & -{\rm i} \end{pmatrix}$, the subscripts denote the ordinal number of atoms, then there will be an evolution:

$$\begin{aligned} & a|gg\rangle_{45} + {\rm i}b|ge\rangle_{45} + {\rm i}c|eg\rangle_{45} - d|ee\rangle_{45} \\ \longrightarrow\ & a|gg\rangle_{45} + b|ge\rangle_{45} + c|eg\rangle_{45} + d|ee\rangle_{45}, \end{aligned} \quad (18)$$

where we have discarded the global phase factor, and the state showed in Eq.(18) is the desired state.

Thus we achieve the teleportation procedure successfully. The total successful probability and fidelity of the output state can both reach 1.0.

4. Discussions and conclusions

Here, we will discuss the feasibility of the current scheme. There is no quantum information transfer between the atoms and the cavity mode. During the course of atoms going through the cavity field, the cavity is only virtually excited and the evolutions do not depend on the cavity state, thus our schemes are insensitive to both the cavity decay and the thermal field, the efficient decoherence time of the cavity is greatly prolonged. In our scheme, the two atoms must interact with the cavity simultaneously. But in reality, we can't achieve simultaneousness in perfect precision. Calculation on the error suggests that it only slightly affects the fidelity of the reconstructed state.[23] So our schemes are reliable by using presently available cavity QED techniques.

In conclusion, simple and feasible physical schemes for teleporting an unknown atomic entangled state based on cavity QED are proposed. We discuss the cases of teleporting a special two-atom entangled state and teleporting an arbitrary two-atom entangled state respectively. Our schemes use a cluster state as the quantum channel, and the schemes are realized by utilizing the separated atomic measurements, which reduce the complexity in experiment, instead of the joint measurements. The successful probability and fidelity of teleportation can both reach 1.0. Moreover, our schemes are free of the effects of the cavity decay and the thermal field. Hence, our scheme is simple and feasible by current technology.

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