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Scheme for Implementing Teleporting an Arbitrary Tripartite Entangled State in Cavity QED

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Abstract We propose to teleport an arbitrary tripartite entangled state in cavity QED. In this scheme, the five-qubit Brown state is chosen as the quantum channel. It has been shown that the teleportation protocol can be completed perfectly with two different measurement methods. In the future, our scheme might be realizable based on present experimental technology.

Keywords Teleportation · Brown state · Cavity QED

1 Introduction

Quantum teleportation [1] is a nice way to transfer an unknown quantum state from the sender (Alice) to the receiver (Bob) via an entangled quantum channel with the help of local operations and classical communications. It has already been experimentally demonstrated with optical system [2–4], nuclear magnetic resonance (NMR) system [5], and ion trap system [6, 7]. Now people have paid much attention to teleporting a two-qubit or multiqubit entangled state due to the fact that it can be used to establish the two-qubit or multiqubit entanglement in a communication network. For teleporting an arbitrary two-qubit state, Lee et al. [8] did not explicitly construct the protocol. Rigolin only considered the quantum channel which is actually the tensor product of a pair of Bell states [9]. Recently, Yeo and Chua have present a genuine four-qubit entangled state $|\chi\rangle$, and shown that it can be used to implement perfect teleportation of an arbitrary two-qubit state [10]. In fact, if we only want to teleport an unknown two-qubit entangled state, the tripartite Greenberger-Horne-Zeilinger (GHZ) state is just an ideal quantum channel [11, 12]. Thus, the required quantum resource is decreased compared with the schemes in [8–10]. In the case of teleporting an arbitrary three-qubit state, Fang et al. [13] have proposed the probabilistic teleportation scheme via three pairs of two-qubit entangled states. It has been shown that quantum teleportation can

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be successfully realized with a certain probability (which is determined by the smallest coefficients of the three entangled pairs) if the receiver adopts an appropriate unitary-reduction strategy. On the other hand, Yang et al. [14] and Lu [15] have shown that if we only want to teleport a tripartite GHZ-class state, the quantum channel only consists of a three-qubit GHZ-class state and a two-qubit entangled state. In other words, the consumed quantum resource is also decreased. Generally speaking, the genuine multiqubit entangled state (e.g. the W state [16], Dicke state [17], cluster state [18, 19] and graph state [20] etc.) has more complex entanglement properties than the two-qubit entangled state and it may also exhibit a surprising robustness with respect to decoherence processes which are unavoidable in the practical system. Recently, Brown et al. [21] have obtained a maximally entangled five-qubit state (namely the Brown state) through an extensive numerical optimization procedure which can be expressed as

$$|B_5\rangle_{12345} = \frac{1}{2}(|gge\rangle|\psi^+\rangle + |geg\rangle|\phi^-\rangle + |egg\rangle|\psi^-\rangle + |eee\rangle|\phi^+\rangle)_{12345}, \tag{1}$$

where

$$|\phi^\pm\rangle = \frac{1}{\sqrt{2}}(|gg\rangle \pm |ee\rangle), \tag{2}$$

$$|\psi^\pm\rangle = \frac{1}{\sqrt{2}}(|ge\rangle \pm |eg\rangle). \tag{3}$$

It exhibits genuine multipartite entanglement and it also has the maximal one-partite and two-partite entanglement between different subsets. Muralidharan et al. [22] have proposed to implement perfect teleportation, quantum state sharing and dense coding with the Brown state. Inspired by their scheme, we have also proposed the controlled teleportation and dense coding scheme via the Brown state [23]. In this paper we will show that it can also be used to teleport an arbitrary tripartite entangled state. In our scheme, two different measurement methods are discussed and both of the successful probability is one. In cavity QED, we will propose to distinguish the Brown state and then implement the teleportation protocol.

2 Teleportation of an Arbitrary Tripartite Entangled State

We assume that Alice has three qubits a, b and c in the general tripartite entangled state as follows [24]

$$|\psi_3\rangle_{abc} = \alpha|gge\rangle_{abc} + \beta|geg\rangle_{abc} + \gamma|egg\rangle_{abc} + \delta|eee\rangle_{abc}, \tag{4}$$

where $\alpha,\ \beta,\ \gamma$ and δ are the unknown complex numbers such as that $|\alpha|^2 + |\beta|^2 + |\gamma|^2 + |\delta|^2 = 1$. Here, if we take $\alpha = \beta = \gamma = \delta = 1/2$, it just reduces to the even parity state [25], which is local equivalent to the tripartite GHZ state. On the other hand, if we take $\alpha = 0$, $\beta = \gamma = \delta = 1/\sqrt{3}$, it will be the well-known W state. In general, its entanglement properties are not completely identical to either the GHZ state or W state. It has double features of both the GHZ state and W state simultaneously. In [26], Jia et al. have prepared this tripartite entangled state and proposed to implement perfect teleportation and dense coding with it in cavity QED. In order to teleport the tripartite entangled state, we assume that Alice and Bob initially share the genuine five-qubit Brown state $|B_5\rangle_{12345}$, where Alice has qubits 4 and 5, while qubits 1, 2 and 3 are with Bob. Now we can rewrite the state of the whole system as

$$|\psi_3\rangle_{abc}|B_5\rangle_{12345} = \frac{1}{4}\sum_{i,j}|B_5^{ij}\rangle_{abc45}|\psi_3^{ij}\rangle_{123} \quad (i, j = 0, 1, 2, 3), \tag{5}$$

where

$$|B_5^{ij}\rangle_{abc45} = (\sigma_a^i \otimes \sigma_b^j)|B_5^{00}\rangle_{abc45}, \tag{6}$$

$$|B_5^{00}\rangle_{abc45} = \frac{1}{2}(|gge\rangle|\psi^+\rangle + |geg\rangle|\phi^-\rangle + |egg\rangle|\psi^-\rangle + |eee\rangle|\phi^+\rangle)_{abc45}, \tag{7}$$

$$|\psi_3^{ij}\rangle_{123} = (\sigma_1^i \otimes \sigma_2^j)|\psi_3^{00}\rangle_{123}, \tag{8}$$

$$|\psi_3^{00}\rangle_{123} = \alpha|gge\rangle_{123} + \beta|geg\rangle_{123} + \gamma|egg\rangle_{123} + \delta|eee\rangle_{123}. \tag{9}$$

Here the local operation σ_a^i represents that we perform σ^i on qubit a (where $\sigma^0 = I$ is the identity operator, $\sigma^1 = \sigma_x$, $\sigma^2 = i\sigma_y$ and $\sigma^3 = \sigma_z$ are the Pauli operators). Now Alice can make a von Neumann-type measurement using the five-qubit Brown states $\{|B_5^{ij}\rangle_{abc45},\ i, j = 0, 1, 2, 3\}$, and then convey her results to Bob by sending five bits of classical information. Bob can then convert the state of his qubits 1, 2 and 3 to that of qubits a, b and c by applying appropriate local unitary transformations.

As we know, the joint Bell-state measurement or multiqubit measurement is the key step in quantum teleportation. In general, the difficultly of implementing joint multiqubit measurement increases with the number of qubits. In experiment, the joint Bell-state measurement can be more easily to realize than the multiqubit measurement. Considering this fact, we assume that Alice makes the Bell-state measurement instead of the five-qubit Brown state measurement. In this case, we can rewrite the state of the whole system as follows

$$\begin{aligned}
&|\psi\rangle_{abc12345}\\
&\quad = \frac{1}{4}[|\phi^+\rangle_{a4}|\phi^+\rangle_{b5}(\alpha|ee\rangle_{c2}|\psi^+\rangle_{13} + \beta|gg\rangle_{c2}|\phi^+\rangle_{13} - \gamma|gg\rangle_{c2}|\phi^-\rangle_{13} - \delta|ee\rangle_{c2}|\psi^-\rangle_{13})\\
&\quad + |\phi^+\rangle_{a4}|\phi^-\rangle_{b5}(\alpha|ee\rangle_{c2}|\psi^+\rangle_{13} - \beta|gg\rangle_{c2}|\phi^+\rangle_{13} - \gamma|gg\rangle_{c2}|\phi^-\rangle_{13} + \delta|ee\rangle_{c2}|\psi^-\rangle_{13})\\
&\quad + |\phi^-\rangle_{a4}|\phi^+\rangle_{b5}(\alpha|ee\rangle_{c2}|\psi^+\rangle_{13} + \beta|gg\rangle_{c2}|\phi^+\rangle_{13} + \gamma|gg\rangle_{c2}|\phi^-\rangle_{13} + \delta|ee\rangle_{c2}|\psi^-\rangle_{13})\\
&\quad + |\phi^-\rangle_{a4}|\phi^-\rangle_{b5}(\alpha|ee\rangle_{c2}|\psi^+\rangle_{13} - \beta|gg\rangle_{c2}|\phi^+\rangle_{13} + \gamma|gg\rangle_{c2}|\phi^-\rangle_{13} - \delta|ee\rangle_{c2}|\psi^-\rangle_{13})\\
&\quad + |\phi^+\rangle_{a4}|\psi^+\rangle_{b5}((\alpha|eg\rangle_{c2}|\phi^+\rangle_{13} + \beta|ge\rangle_{c2}|\psi^+\rangle_{13} - \gamma|ge\rangle_{c2}|\psi^-\rangle_{13} - \delta|eg\rangle_{c2}|\phi^-\rangle_{13})\\
&\quad + |\phi^+\rangle_{a4}|\psi^-\rangle_{b5}((\alpha|eg\rangle_{c2}|\phi^+\rangle_{13} - \beta|ge\rangle_{c2}|\psi^+\rangle_{13} - \gamma|ge\rangle_{c2}|\psi^-\rangle_{13} + \delta|eg\rangle_{c2}|\phi^-\rangle_{13})\\
&\quad + |\phi^-\rangle_{a4}|\psi^+\rangle_{b5}((\alpha|eg\rangle_{c2}|\phi^+\rangle_{13} + \beta|ge\rangle_{c2}|\psi^+\rangle_{13} + \gamma|ge\rangle_{c2}|\psi^-\rangle_{13} + \delta|eg\rangle_{c2}|\phi^-\rangle_{13})\\
&\quad + |\phi^-\rangle_{a4}|\psi^-\rangle_{b5}((\alpha|eg\rangle_{c2}|\phi^+\rangle_{13} - \beta|ge\rangle_{c2}|\psi^+\rangle_{13} + \gamma|ge\rangle_{c2}|\psi^-\rangle_{13} - \delta|eg\rangle_{c2}|\phi^-\rangle_{13})\\
&\quad + |\psi^+\rangle_{a4}|\phi^+\rangle_{b5}(-\alpha|eg\rangle_{c2}|\phi^-\rangle_{13} - \beta|ge\rangle_{c2}|\psi^-\rangle_{13} + \gamma|ge\rangle_{c2}|\psi^+\rangle_{13} + \delta|eg\rangle_{c2}|\phi^+\rangle_{13})\\
&\quad + |\psi^+\rangle_{a4}|\phi^-\rangle_{b5}(-\alpha|eg\rangle_{c2}|\phi^-\rangle_{13} + \beta|ge\rangle_{c2}|\psi^-\rangle_{13} + \gamma|ge\rangle_{c2}|\psi^+\rangle_{13} - \delta|eg\rangle_{c2}|\phi^+\rangle_{13})\\
&\quad + |\psi^-\rangle_{a4}|\phi^+\rangle_{b5}(-\alpha|eg\rangle_{c2}|\phi^-\rangle_{13} - \beta|ge\rangle_{c2}|\psi^-\rangle_{13} - \gamma|ge\rangle_{c2}|\psi^+\rangle_{13} - \delta|eg\rangle_{c2}|\phi^+\rangle_{13})\\
&\quad + |\psi^-\rangle_{a4}|\phi^-\rangle_{b5}(-\alpha|eg\rangle_{c2}|\phi^-\rangle_{13} + \beta|ge\rangle_{c2}|\psi^-\rangle_{13} - \gamma|ge\rangle_{c2}|\psi^+\rangle_{13} + \delta|eg\rangle_{c2}|\phi^+\rangle_{13})
\end{aligned}$$

$$+ |\psi^+\rangle_{a4}|\psi^+\rangle_{b5}(-\alpha|ee\rangle_{c2}|\psi^-\rangle_{13} - \beta|gg\rangle_{c2}|\phi^-\rangle_{13} + \gamma|gg\rangle_{c2}|\phi^+\rangle_{13} + \delta|ee\rangle_{c2}|\psi^+\rangle_{13})$$
$$+ |\psi^+\rangle_{a4}|\psi^-\rangle_{b5}(-\alpha|ee\rangle_{c2}|\psi^-\rangle_{13} + \beta|gg\rangle_{c2}|\phi^-\rangle_{13} + \gamma|gg\rangle_{c2}|\phi^+\rangle_{13} - \delta|ee\rangle_{c2}|\psi^+\rangle_{13})$$
$$+ |\psi^-\rangle_{a4}|\psi^+\rangle_{b5}(-\alpha|ee\rangle_{c2}|\psi^-\rangle_{13} - \beta|gg\rangle_{c2}|\phi^-\rangle_{13} - \gamma|gg\rangle_{c2}|\phi^+\rangle_{13} - \delta|ee\rangle_{c2}|\psi^+\rangle_{13})$$
$$+ |\psi^-\rangle_{a4}|\psi^-\rangle_{b5}(-\alpha|ee\rangle_{c2}|\psi^-\rangle_{13} + \beta|gg\rangle_{c2}|\phi^-\rangle_{13} - \gamma|gg\rangle_{c2}|\phi^+\rangle_{13} + \delta|ee\rangle_{c2}|\psi^+\rangle_{13})]. \tag{10}$$

Now, Alice will make two joint Bell-state measurements on qubits a, 4 and b, 5. Without loss of generality, we assume that the measurement outcome is $|\psi^+\rangle_{a4}|\phi^-\rangle_{b5}$. Then the state of qubits c, 1, 2 and 3 will collapse into

$$-\alpha|eg\rangle_{c2}|\phi^-\rangle_{123} + \beta|ge\rangle_{c2}|\psi^-\rangle_{13} + \gamma|ge\rangle_{c2}|\psi^+\rangle_{123} - \delta|eg\rangle_{c2}|\phi^+\rangle_{13}. \tag{11}$$

Then she makes a single-qubit measurement on qubit c in the following basis

$$|+\rangle_c = \frac{1}{\sqrt{2}}(|g\rangle_c + |e\rangle_c), \tag{12}$$

$$|-\rangle_c = \frac{1}{\sqrt{2}}(|g\rangle_c - |e\rangle_c). \tag{13}$$

If the measurement outcome is $|+\rangle_c$, qubits 1, 2 and 3 will collapse into

$$-\alpha|g\rangle_2|\phi^-\rangle_{13} + \beta|e\rangle_2|\psi^-\rangle_{13} + \gamma|e\rangle_2|\psi^+\rangle_{13} - \delta|g\rangle_2|\phi^+\rangle_{13}. \tag{14}$$

Then Alice sends all of the measurement outcomes including the Bell-state measurements on qubits a, 4 and b, 5 and the single-qubit measurement on qubit c to Bob. In order to recover the initial state, firstly Bob can make the unitary transformations as follows:

$$|\phi^-\rangle_{13} \to |gg\rangle_{13}, \tag{15}$$

$$|\phi^+\rangle_{13} \to |ee\rangle_{13}, \tag{16}$$

$$|\psi^-\rangle_{13} \to |ge\rangle_{13}, \tag{17}$$

$$|\psi^+\rangle_{13} \to |eg\rangle_{13}, \tag{18}$$

which will lead the state of qubits 1, 2 and 3 to

$$-\alpha|ggg\rangle_{123} + \beta|gee\rangle_{123} + \gamma|eeg\rangle_{123} - \delta|ege\rangle_{123}. \tag{19}$$

Now Bob can make the local operations $\sigma_3^1\sigma_2^3$ and two controlled-not operations C_{12} and C_{13}, then can reconstruct the original state on his own qubits perfectly.

If Alice's measurement outcome on qubit c is $|-\rangle_c$, the state of qubits 2, 3 and 4 will be

$$\alpha|g\rangle_2|\phi^-\rangle_{13} + \beta|e\rangle_2|\psi^-\rangle_{13} + \gamma|e\rangle_2|\psi^+\rangle_{13} + \delta|g\rangle_2|\phi^+\rangle_{13}. \tag{20}$$

In this case, Bob can also recover the original state with the similar procedure. The only difference is that Bob only needs make the local operation σ_3^1 instead of $\sigma_3^1\sigma_2^3$. For Alice's other measurement outcomes, Bob must operate relevant unitary transformations and can always succeed in recovering the original state.

3 Physical Implementation

The cavity QED system is one of the most possible candidates for engineering quantum entanglement in quantum information processing (QIP). In most previous schemes the cavity is used to store the quantum information and transfer it back to the atomic system, thus the cavity decay is one of the main obstacles to implement QIP in cavity QED. Recently Zheng [27] have proposed a novel scheme in which two identical atoms simultaneously interact with a nonresonant cavity field and a strong classical field. The photon-number dependent parts in the interaction Hamiltonian of the system are canceled and thus the scheme is insensitive to both the cavity decay and thermal field, which is of importance in view of experiment. Following this idea, we consider N identical two-level atoms simultaneously interacting with a single-mode cavity and driven by a strong classical field. In the rotating wave approximation, the Hamiltonian of the system is

$$H = \omega_0 \sum_{j=1}^{N} S_z^j + \omega_a a^\dagger a + \sum_{j=1}^{N} [g(a^\dagger S_j^- + a S_j^+) + \Omega(S_j^+ e^{-i\omega t} + S_j^- e^{i\omega t})], \tag{21}$$

where $S_z^j = \frac{1}{2}(|e_j\rangle\langle e_j| - |g_j\rangle\langle g_j|)$, $S_j^+ = |e_j\rangle\langle g_j|$, $S_j^- = |g_j\rangle\langle e_j|$ with $|g_j\rangle$ and $|e_j\rangle$ being the ground and excited states of the jth atom, $a^\dagger$ and a are the creation and annihilation operators of the cavity mode, g is the atom-cavity coupling strength, Ω is the Rabi frequency, ω_0, ω_a and ω are the atomic transition frequency, the cavity frequency and the frequency of the classical field. Supposing $\omega_0 = \omega$, in the interaction picture the interaction Hamiltonian is

$$H_i = \sum_{j=1}^{N} [g(e^{-i\delta t} a^\dagger S_j^- + e^{i\delta t} a S_j^+) + \Omega(S_j^+ e^{-i\omega t} + S_j^- e^{i\omega t})], \tag{22}$$

where $\delta = \omega_0 - \omega_a$ is the detuning between the atomic transition frequency and the cavity frequency. In the strong driving regime $\Omega \gg \delta \gg g$, there is no energy exchange between the atomic system and the cavity. Then in the interaction picture, the effective interaction Hamiltonian is [27]

$$H_e = \frac{\lambda}{2}\left[\sum_{j=1}^{N}(|e_j\rangle\langle e_j| + |g_j\rangle\langle g_j|) + \sum_{j,k=1, j\neq k}^{N} (S_j^+ S_k^- + S_j^+ S_k^+ + H.C.)\right], \tag{23}$$

where $\lambda = g^2/2\delta$. It is noted that the effective Hamiltonian is independent of the cavity field state, allowing it to be in a thermal state. Then the evolution operator of the system is

$$U(t) = e^{-iH_0 t} e^{-iH_e t}, \tag{24}$$

where

$$H_0 = \Omega \sum_{j=1}^{N} (S_j^+ + S_j^-). \tag{25}$$

In Ref. [23] we have prepared the Brown state and also implement the joint Bell-state measurement in cavity QED. Here, let's discuss how to distinguish the Brown state as shown (6). Firstly we perform the rotation $|e\rangle_4 \to i|e\rangle_4$ on atom 4 and then we let atoms 4 and 5 interact with the single-mode cavity and driven by the classical field. After the interaction time

$t_1 = \pi/(4\lambda)$ we can obtain the following evolution

$$|B_5^{00}\rangle_{abc45} \to \frac{1}{2}(-i|ggeeg\rangle + |geggg\rangle + |eggge\rangle - i|eeeee\rangle)_{abc45}. \tag{26}$$

Secondly, we then let atoms b, c and 4 interact with the same single-mode cavity and driven by the classical field. If we choose the interaction time appropriately so that $\lambda t_2 = (2k + 1/4)\pi$ and $\Omega t_2 = (2m + 3/4)\pi$, the state evolution is

$$|B_5^{00}\rangle_{abc45} \to \frac{1}{\sqrt{2}}(|ggeeg\rangle + |eeeee\rangle)_{abc45}. \tag{27}$$

After performing the rotation $|g\rangle_5 \to i|g\rangle_5$ on qubit a, we then let qubits a, b and 5 undergo the same evolution as qubits b, c and 4, and can obtain the following evolution

$$|B_5^{00}\rangle_{abc45} \to |ggeeg\rangle_{abc45}. \tag{28}$$

It is noted that we have discarded the global phase factor during the evolution process for simplicity. With the same procedure, we can also transform the other orthogonal Brown states $\{|B_5^{ij}\rangle_{abc45},\ i, j = 0, 1, 2, 3\}$ into the product states $\{\{|gg\rangle_{45}, |ge\rangle_{45}, |eg\rangle_{45}, |ee\rangle_{45}\} \otimes \{|ggg\rangle_{abc}, |ege\rangle_{abc}, |eeg\rangle_{abc}, |gee\rangle_{abc}\}\}$. Hence, we can distinguish the Brown states $\{|B_5^{ij}\rangle_{abc45},\ i, j = 0, 1, 2, 3\}$ by detecting four atoms (4, 5, and arbitrary two atoms of a, b and c) separately, and then we can implement the teleportation scheme in cavity QED.

4 Conclusions

In summary, we have proposed to teleport an arbitrary tripartite entangled state with the five-qubit Brown state. In cavity QED, we have proposed to distinguish the five-qubit Brown state and demonstrated the feasibility of our scheme. Compared with the previous schemes [14, 15], our scheme has distinct advantages. Firstly, the teleported state in our scheme is more general and it includes all of the possible tripartite entangled states. However, Yang et al. [14] and Lu [15] only considered teleportation of the tripartite GHZ-class state. Secondly, the entangled quantum channel we have used is the five-qubit Brown state. In [14, 15] the tense product of a GHZ-class state and an two-qubit entangle state are used as the quantum channel. Thus, our scheme might be more robust against decoherence than [14] and [15]. In the future, we hope that our scheme can be realized with present experimental technology.

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