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Teleportation of an n-bit one-photon and vacuum entangled GHZ cavity-field state*

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A scheme for teleporting an arbitrary n-bit one-photon and vacuum entangled Greenberger–Horne–Zeilinger (GHZ) state is proposed. In this scheme, the maximum entanglement GHZ state is used as a quantum channel. We find a method of distinguishing four Bell states just by detecting the atomic states three times, which is irrelevant to the qubit number of the state to be teleported.

Keywords: teleportation, multi-atom-cavity system, one-photon and vacuum entangled GHZ state, atom state detection
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1. Introduction

Quantum teleportation is one of the most prominent physical phenomena in quantum information theory, and also one of the important ways of transmitting quantum information. It is originally proposed by Bennett *et al*[1] in 1993; they used an entanglement state as a quantum channel to teleport an unknown quantum state from one party to another via both Bell basis measurement and classical communication. Quantum teleportation has received much attention both theoretically and experimentally in recent years, and a lot of schemes[2−5] for teleportation have been put forward. According to the quantum state being a finite-dimensional or infinite-dimensional Hilbert space variable, it can be determined to be discrete variable or continuous variable quantum teleportation, respectively; while according to the entanglement degree of the quantum state used as a quantum channel being maximum or medium, it can be determined to be criterion or probability quantum teleportation respectively.[6−13] Greenberger–Horne–Zeilinger (GHZ) states are an important form of the entanglement states and play an important role in quantum information encode. At present, through cavity quantum electrodynamics technology one can operate and control cavity–field state of single photon and interior state of single atom.[14,15] A one-photon and vacuum entangled GHZ or superposed state in quantum information process used as the basic physical element (bit) has gained many achievements.[16,17] An atom and one photon interacting with each other in a high Q cavity make the quantum state evolve or transform, which has become hotspots in this field. This simplest physical system, in which single photon is used as flying qubit and single atom as a stationary qubit, and the high Q cavity as an atom–photon interaction place, is the best candidate in performing the quantum information process. In this paper, a scheme for teleporting an arbitrary n-bit one-photon and vacuum entangled GHZ state is proposed. As is well known, distinguishing four Bell states is the key step to successfully teleport a quantum state. Our teleportation scheme only requires detecting the atom states three times, and is irrelevant to the qubit number of the state to be teleported. The first atom is used to cross the two cavities under the non-resonant atom–cavity interaction to realize a nondestructive measurement on the cavity–field through the detection of atomic state; and the second and the third atoms are used under resonant atom–cavity interac-

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tion to realize information transference between atoms and cavities. Finally we find a method of distinguishing four cavity–field Bell states, which consist of vacuum and one-photon state, by which we can obtain cavity–field Bell states via measuring atomic states. The rest of this paper is organized as follows: in Section 2 we discuss the teleportation of an unknown one-photon and vacuum superposition state in a cavity. In Section 3 we discuss the teleportation of an unknown one-photon and vacuum entangled GHZ state in two cavities, and generalize it to an n-bit entangled GHZ state. Finally a brief summary of our results is given in Section 4.

2. Teleportation of an unknown one-photon and vacuum superposition state in a cavity

Suppose that an unknown state $|\Psi\rangle_{\rm A} = \alpha|0\rangle + \beta|1\rangle$ in cavity A is transmitted to cavity C. According to the teleportation idea proposed by Bennett *et al*,[1] the first step is to establish a quantum channel, and without loss generality, the state of this channel is assumed to be described by $|\Phi\rangle_{\rm BC} = (|00\rangle + |11\rangle)/\sqrt{2}$. The state of the combined system (cavity A plus channel cavities B and C) can be rewritten as

$$\begin{aligned}|\Psi\rangle_{\rm A}|\Phi\rangle_{\rm BC} = \frac{1}{2}[&|\Psi^{(+)}\rangle_{\rm AB}(\beta|0\rangle_{\rm C} + \alpha|1\rangle_{\rm C}) \\ &+ |\Psi^{(-)}\rangle_{\rm AB}(-\beta|0\rangle_{\rm C} + \alpha|1\rangle_{\rm C}) \\ &+ |\Phi^{(+)}\rangle_{\rm AB}(\alpha|0\rangle_{\rm C} + \beta|1\rangle_{\rm C}) \\ &+ |\Phi^{(-)}\rangle_{\rm AB}(\alpha|0\rangle_{\rm C} - \beta|1\rangle_{\rm C})], \end{aligned} \quad (1)$$

where

$$\begin{aligned}|\Psi^{(\pm)}\rangle_{\rm AB} &= \frac{1}{\sqrt{2}}[|01\rangle_{\rm AB} \pm |10\rangle_{\rm AB}]\,, \\ |\Phi^{(\pm)}\rangle_{\rm AB} &= \frac{1}{\sqrt{2}}[|00\rangle_{\rm AB} \pm |11\rangle_{\rm AB}]\,. \end{aligned} \quad (2)$$

Measuring Bell states in cavities A and B is the key step to realize the physical process of teleportation, so we need to perform Bell state measurements in cavities A and B. The cavity C projects into one of the four states: $|\psi\rangle_{\rm C} = \alpha|0\rangle + \beta|1\rangle$, $|\psi\rangle_{\rm C} = \alpha|0\rangle - \beta|1\rangle$, $|\psi\rangle_{\rm C} = \beta|0\rangle + \alpha|1\rangle$, and $|\psi\rangle_{\rm C} = \beta|0\rangle - \alpha|1\rangle$, and then the state in cavity C is transformed according to measurements, finally the cavity C is in the initial state of cavity A. Teleporting the cavity-field state is successful now. It needs some clarification that these physical processes are conducted in one laboratory, so any classical communication is not required.

In the following, we pay attention to the method by which we can distinguish different kinds of Bell states in cavities A and B: $|\Psi^{(\pm)}\rangle_{\rm AB}$ and $|\Phi^{(\pm)}\rangle_{\rm AB}$ in Eq.(2). The first step is to let atom 1 in ground state go through cavities A and B successively under the non-resonant atom–cavity interaction, and control the interaction time according to the transformation $|e\rangle|0\rangle \to -|g\rangle|0\rangle$, $|e\rangle|1\rangle \to -|e\rangle|1\rangle$, $|g\rangle|0\rangle \to |e\rangle|0\rangle$, and $|g\rangle|1\rangle \to |g\rangle|1\rangle$, which was proposed by Davidovich *et al*[18] and Brune *et al*,[19] thereby we realize a nondestructive measurement, and can distinguish four Bell states of two kinds: $|\Psi\rangle_{\rm AB}$ and $|\Phi\rangle_{\rm AB}$. For being clear at a glance, after atom 1 has flown away from the cavities A and B, we can describe the state evolution of the whole system in formula language as follows:

$$\begin{aligned}|g_1\rangle|\Psi^{(\pm)}\rangle_{\rm AB} &\xrightarrow{\rm A} \frac{1}{\sqrt{2}}[|e_1\rangle|01\rangle_{\rm AB} \pm |g_1\rangle|10\rangle_{\rm AB}] \\ &\xrightarrow{\rm B} \frac{1}{\sqrt{2}}|e_1\rangle[|01\rangle_{\rm AB} \mp |10\rangle_{\rm AB}]\,, \\ |g_1\rangle|\Phi^{(\pm)}\rangle_{\rm AB} &\xrightarrow{\rm A} \frac{1}{\sqrt{2}}[|e_1\rangle|00\rangle_{\rm AB} \pm |g_1\rangle|11\rangle_{\rm AB}] \\ &\xrightarrow{\rm B} \frac{1}{\sqrt{2}}|g_1\rangle[|00\rangle_{\rm AB} \mp |11\rangle_{\rm AB}]. \end{aligned} \quad (3)$$

Through the measurement of atom 1 we know that ground state of atom 1 corresponds to $|\Phi^{(\pm)}\rangle_{\rm AB}$, the excited state corresponds to $|\Psi^{(\pm)}\rangle_{\rm AB}$. So we have identified two kinds of Bell states. The second step is to let atom 2 and 3 in ground state pass through cavities A and B respectively under the resonant atom–cavity interaction, and control the interaction time according to $t = \pi/(2\lambda)$[20] in order to transfer the information in the cavities to the atom. And then let the atoms 2 and 3 go through the Ramsey microwave zone. Thus the states of the atoms again undergo the state transformation as follows:[17]

$$|e\rangle \xrightarrow{R} \frac{1}{\sqrt{2}}(|e\rangle + |g\rangle), \quad |g\rangle \xrightarrow{R} \frac{1}{\sqrt{2}}(|e\rangle - |g\rangle). \quad (4)$$

Through the measurement of the states of atoms 2 and 3 we can distinguish the '+' and '–' in each kind of Bell states: $|\Phi^{(-)}\rangle_{\rm AB}(|\Psi^{(-)}\rangle_{\rm AB})$ and $|\Phi^{(+)}\rangle_{\rm AB}(|\Psi^{(+)}\rangle_{\rm AB})$.

The state evolution in the whole process can be described as follows:

$$\begin{aligned}|g_2g_3\rangle|\Psi^{(\pm)}\rangle_{\rm AB} &\xrightarrow{\rm A,B} |00\rangle_{\rm AB}\frac{1}{\sqrt{2}}[|g_2e_3\rangle \pm |e_2g_3\rangle] \\ &\xrightarrow{\rm R} \begin{cases} \dfrac{1}{\sqrt{2}}[|e_2e_3\rangle - |g_2g_3\rangle] \\ \dfrac{1}{\sqrt{2}}[|e_2g_3\rangle - |g_2e_3\rangle], \end{cases}\end{aligned}$$

$$|g_2g_3\rangle|\Phi^{(\pm)}\rangle_{\rm AB}\xrightarrow{\rm A,B}|00\rangle_{\rm AB}\frac{1}{\sqrt{2}}[|g_2g_3\rangle\pm|e_2e_3\rangle]$$
$$\xrightarrow{\rm R}\begin{cases}\frac{1}{\sqrt{2}}[|e_2e_3\rangle+|g_2g_3\rangle]\\ \frac{1}{\sqrt{2}}[|e_2g_3\rangle+|g_2e_3\rangle].\end{cases}\quad(5)$$

Through Eqs.(3) and (5) we know the associative relationships between states of three atoms and four Bell states as follows:

$$\frac{1}{\sqrt{2}}|e_1\rangle[|e_2e_3\rangle-|g_2g_3\rangle]\rightarrow|\Psi^{(-)}\rangle,$$
$$\frac{1}{\sqrt{2}}|e_1\rangle[|e_2g_3\rangle-|g_2e_3\rangle]\rightarrow|\Psi^{(+)}\rangle,\quad(6)$$
$$\frac{1}{\sqrt{2}}|g_1\rangle[|e_2e_3\rangle+|g_2g_3\rangle]\rightarrow|\Phi^{(-)}\rangle,$$
$$\frac{1}{\sqrt{2}}|g_1\rangle[|e_2g_3\rangle+|g_2e_3\rangle]\rightarrow|\Phi^{(+)}\rangle.\quad(7)$$

In this way, we can distinguish four Bell states by measuring states of the three atoms.

The last step of teleportation is to transform the quantum state in cavity C according to the measurements. When we obtain $|\Phi^{(-)}\rangle$, the phase of the cavity–field state is needed to transform,[21] i.e. let one atom go through cavity C within a suitable time under the non-resonant interaction with the cavity; when we obtain $|\Psi^{(+)}\rangle$, we need controlled-NOT gate 'CNOT' to operate the cavity, or use atom–cavity CNOT gate, its function is $|g\rangle|0\rangle\leftrightarrow|g\rangle|1\rangle$; if we have $|\Psi^{(-)}\rangle$ we need 'PHASE' and 'CNOT' both to operate; but when we obtain $|\Phi^{(+)}\rangle$ we need not transform it any more. The whole process of teleportation is ended here now.

3. Teleportation of an unknown one-photon and vacuum entangled GHZ state in two cavities

Suppose that in cavities A and B there is an entangled GHZ state $|\Psi\rangle_{\rm AB}=\alpha|00\rangle_{\rm AB}+\beta|11\rangle_{\rm AB}$. We will teleport it to cavities M and N. Therefore we establish a quantum channel through cavities C, M and N, that is $|\Psi\rangle_{\rm CMN}=\frac{1}{\sqrt{2}}[|000\rangle_{\rm CMN}+|111\rangle_{\rm CMN}]$, the combined state of these five cavities A, B, C, M and N can be expressed as follows:

$$\begin{aligned}|\Psi\rangle_{\rm ABCMN}&=|\Psi\rangle_{\rm AB}|\Psi\rangle_{\rm CMN}\\&=[\alpha|00\rangle_{\rm AB}+\beta|11\rangle_{\rm AB}]\\&\quad\times\frac{1}{\sqrt{2}}[|000\rangle_{\rm CMN}+|111\rangle_{\rm CMN}]\\&=\frac{1}{2}[|\Psi^{(+)}\rangle_{\rm ABC}(\beta|00\rangle_{\rm MN}+\alpha|11\rangle_{\rm MN})\\&\quad+|\Psi^{(-)}\rangle_{\rm ABC}(-\beta|00\rangle_{\rm MN}+\alpha|11\rangle_{\rm MN})\\&\quad+|\Phi^{(+)}\rangle_{\rm ABC}(\alpha|00\rangle_{\rm MN}+\beta|11\rangle_{\rm MN})\\&\quad+|\Phi^{(-)}\rangle_{\rm ABC}(\alpha|00\rangle_{\rm MN}-\beta|11\rangle_{\rm MN})],\end{aligned}\quad(8)$$

where

$$|\Psi^{(\pm)}\rangle_{\rm ABC}=\frac{1}{\sqrt{2}}[|001\rangle_{\rm ABC}\pm|110\rangle_{\rm ABC}];$$
$$|\Phi^{(\pm)}\rangle_{\rm ABC}=\frac{1}{\sqrt{2}}[|000\rangle_{\rm ABC}\pm|111\rangle_{\rm ABC}].\quad(9)$$

Through Eq.(8) it is known that by identifying the states in cavities A, B and C, the states in cavities M and N collapse into one of the following four states:

$$|\Psi\rangle_{\rm MN}=\alpha|00\rangle_{\rm MN}+\beta|11\rangle_{\rm MN},$$
$$|\Psi\rangle_{\rm MN}=\alpha|00\rangle_{\rm MN}-\beta|11\rangle_{\rm MN},$$
$$|\Psi\rangle_{\rm MN}=\beta|00\rangle_{\rm MN}+\alpha|11\rangle_{\rm MN},$$

and

$$|\Psi\rangle_{\rm MN}=-\beta|00\rangle_{\rm MN}+\alpha|11\rangle_{\rm MN}.$$

Similar to the preceding section, in order to successfully teleport the entangled GHZ state, the key step is to distinguish four Bell states in the expression (9). If we consider only the qubits in cavities B and C in the expression (9), we can see that the expression (9) is the same as the expression (2). Therefore we can follow the way of both measuring the states in cavities B and C and transforming the states in cavity M or N in the preceding section. The detail is as follows. The first step is to use atom 1 to distinguish $|\Psi^{(\pm)}\rangle_{\rm ABC}$ and $|\Phi^{(\pm)}\rangle_{\rm ABC}$, let atom 1 go through cavities B and C successively under the non-resonant interaction with the cavity. After the atom has crossed the cavity the state evolves as follows:

$$\begin{aligned}|g_1\rangle|\Psi^{(\pm)}\rangle&\xrightarrow{\rm B}\frac{1}{\sqrt{2}}[|e_1\rangle|001\rangle_{\rm ABC}\pm|g_1\rangle|110\rangle_{\rm ABC}]\\&\xrightarrow{\rm C}\frac{1}{\sqrt{2}}|e_1\rangle[|001\rangle_{\rm ABC}\mp|110\rangle_{\rm ABC}],\\|g_1\rangle|\Phi^{(\pm)}\rangle&\xrightarrow{\rm B}\frac{1}{\sqrt{2}}[|e_1\rangle|000\rangle_{\rm ABC}\pm|g_1\rangle|111\rangle_{\rm ABC}]\\&\xrightarrow{\rm C}\frac{1}{\sqrt{2}}|g_1\rangle[|000\rangle_{\rm ABC}\mp|111\rangle_{\rm ABC}].\end{aligned}\quad(10)$$

According to the expression (10), by measuring the states of atom 1, we know that $|e_1\rangle\rightarrow|\psi^{(\pm)}\rangle$; $|g_1\rangle\rightarrow|\phi^{(\pm)}\rangle$. The second step is to let atoms 2 and 3 in the ground state go through cavities B and C respectively, and control the time for atoms to cross the

cavities according to $t = \pi/(2\lambda)$.[20] The transformation of system states can be expressed as

$$|g_2g_3\rangle|\,\Psi^{(\pm)}\rangle_{\rm BC} \xrightarrow{\rm B,C} |\frac{1}{\sqrt{2}}\,|00\rangle_{\rm BC}\,[|g_2e_3\rangle \pm |e_2g_3\rangle],$$
$$|g_2g_3\rangle|\,\Phi^{(\pm)}\rangle_{\rm BC} \xrightarrow{\rm B,C} |\frac{1}{\sqrt{2}}\,|00\rangle_{\rm BC}\,[|g_2g_3\rangle \pm |e_2e_3\rangle]. \quad (11)$$

The atoms fly away from the cavity, afterwards they go through Ramsey microwave zone.[17] Thus the states of atoms undergo a transformation in Eq.(4). The state evolution in the whole process can be described as follows:

$$\begin{aligned}|g_2g_3\rangle|\,\Psi^{(\pm)}\rangle_{\rm BC} &\xrightarrow{\rm B,C} |00\rangle_{\rm BC}\frac{1}{\sqrt{2}}[|g_2e_3\rangle \pm |e_2g_3\rangle]\\ &\xrightarrow{\rm R} \begin{cases}\frac{1}{\sqrt{2}}[|e_2e_3\rangle - |g_2g_3\rangle]\\ \frac{1}{\sqrt{2}}[|e_2g_3\rangle - |g_2e_3\rangle],\end{cases}\\ |g_2g_3\rangle|\,\Phi^{(\pm)}\rangle_{\rm BC} &\xrightarrow{\rm B,C} |00\rangle_{\rm BC}\frac{1}{\sqrt{2}}[|g_2g_3\rangle \pm |e_2e_3\rangle]\\ &\xrightarrow{\rm R} \begin{cases}\frac{1}{\sqrt{2}}[|e_2e_3\rangle + |g_2g_3\rangle]\\ \frac{1}{\sqrt{2}}[|e_2g_3\rangle + |g_2e_3\rangle].\end{cases}\quad (12)\end{aligned}$$

Thus it is enough to distinguish $|\,\Psi^{(+)}\rangle$ and $|\,\Psi^{(-)}\rangle(|\,\Phi^{(+)}\rangle$ and $|\,\Phi^{(-)}\rangle)$ just according to quantum states in cavities B and C, so we need not to consider the cavity A. Through the expressions (10), (11), and (12) we know the associative relationships between states of three atoms and four Bell states as follows:

$$\begin{aligned}&\frac{1}{\sqrt{2}}|e_1\rangle[|e_2e_3\rangle - |g_2g_3\rangle] \to |\,\Psi^{(-)}\rangle_{\rm ABC},\\ &\frac{1}{\sqrt{2}}|e_1\rangle[|e_2g_3\rangle - |g_2e_3\rangle] \to |\,\Psi^{(+)}\rangle_{\rm ABC}, \quad (13)\\ &\frac{1}{\sqrt{2}}|g_1\rangle[|e_2e_3\rangle + |g_2g_3\rangle] \to |\,\Phi^{(-)}\rangle_{\rm ABC},\\ &\frac{1}{\sqrt{2}}|g_1\rangle[|e_2g_3\rangle + |g_2e_3\rangle] \to |\,\Phi^{(+)}\rangle_{\rm ABC}. \quad (14)\end{aligned}$$

The last step is to make a transformation of quantum states in the cavities M and N. When we obtain $|\,\Phi^{(-)}\rangle$ through measurement, the phase of the cavity–field state needs transforming.[21] Let an atom go through cavity M or N, and let the atom interact non-resonantly with the cavity–field, and control the interaction time to perform the following transformation:

$$|g\rangle|0\rangle_{\rm M} \to |g\rangle|0\rangle_{\rm M}; \quad |g\rangle|1\rangle_{\rm M} \to -|g\rangle|1\rangle_{\rm M}.$$

When we have $|\,\Psi^{(+)}\rangle$, we need 'CNOT' to operate the cavity–field state. If we have $|\,\Psi^{(-)}\rangle$ we need both 'Phase' and 'CNOT' to operate. We can achieve all these goals by using atom–cavity CNOT gate.[17] When we obtain $|\,\Phi^{(+)}\rangle$ we need not transform it any more. Thus an entangled GHZ state is successfully teleported.

When it is needed to teleport a three-bit entangled GHZ state, which consists of one-photon and vacuum in three cavities, one can do it in a similar way as shown below. Similarly these Bell states can be described as

$$|\,\Psi^{(\pm)}\rangle_{\rm ABCD} = \frac{1}{\sqrt{2}}[|0001\rangle_{\rm ABCD} \pm |1110\rangle_{\rm ABCD}]$$

and

$$|\,\Phi^{(\pm)}\rangle_{\rm ABCD} = \frac{1}{\sqrt{2}}[|0000\rangle_{\rm ABCD} \pm |1111\rangle_{\rm ABCD}].$$

Paying attention to these four states, if we consider only the states in cavities C and D, they are standard Bell states the same as the expressions (2) and (9). We also need three atoms and use the above-mentioned method to distinguish these Bell states. There is no doubt that we can generalize this method of teleportation to the case of teleporting the arbitrary multi-qubits of cavity–field states.

4. Conclusions

We discuss in detail a scheme for quantum teleporting one-bit vacuum and one-photon superposition state and two-bit entangled GHZ state. In the scheme the maximum entangled GHZ state is used as a quantum channel. The scheme can be generalized to the teleportation of an arbitrary multi-qubit entangled GHZ state. Comparing with other schemes,[22−25] this scheme has an advantage in Bell states detection. It is required that detecting the atom state is carried out only three times, and it is irrelevant to the qubit number of the state to be teleported. As for 'Phase' transformation and 'CNOT' transformation, we can use existing achievements to realize them.[15,16] This physical model can be completely realized by using the present technology of the cavity QED.

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