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Quantum Teleportation with Linear Cluster-class States*

ZHONG Feng[1], YU Li-zhi[2], LI Chun-shu[1]

(1 *Department of Physics, Hunan University of Science and Engineering, Yongzhou, Hunan* 425100, *China*)

(2 *Department of Physics and Electrics, Fuyang Teachers College, Fuyang, Anhui* 236041, *China*)

Abstract: A scheme for teleportation of an arbitrary two-qubit state using a four-qubit linear cluster-class state is proposed. Quantum teleportation can be successfully realized with a certain probability if the receiver can adopt an appropriate collective unitary transformation after receiving the sender's Bell-state measurement information. The scheme is more practical than previous ones using maximally entangled states as the quantum channel. In addition, an important conclusion is obtained from the above scheme that a maximally four-qubit entangled state (cluster state) is extracted from a single copy of the cluster-class state with the same probability as the teleportation.

Key words: Quantum optics; Teleportation; Cluster-class state; Bell-state measurement; Unitary transformation

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0 Introduction

Entanglement, one of the most striking features of quantum mechanics, not only provides possibilities to test the foundations of quantum physics, but also lies at the heart of the growing field of quantum information science[1-2]. Generaly speaking the more particles that can be entangled, the more clearly nonclassical effects are exhibited[3], and the more useful the states are for quantum applications[4]. Thus exploring and exploiting multipartite entanglement have been attractive. An important class of multipartite entangled states is cluster states[5]. Cluster states have many interesting features. They have a high persistence of entanglement, and can be regarded as an entanglement source for the Greenberger-Horne-Zeilinger (GHZ) states[6] but are more immune to decoherence than them[7]. It has been shown that a new inequality is maximally violated by the four-particle cluster states but not by the four-particle GHZ states[8]. In recent years, the cluster states were widely utilized to achieve various quantum tasks. They can be used to test quantum nonlocality without inequality[8], acting as quantum error-correcting codes[9], and more importantly, constitute a universal resource for one-way quantum computation[4]. Recently, research groups have experimentally realized cluster states with optically trapped neutral atoms[10] and flying polarized photons[11-12], and demonstrated the feasibility of one-way quantum computation in optical systems[13-14].

Quantum teleportation[15], a prime example of a quantum information processing task that teleports an unknown quantum state from one site to another site, is a remarkable application of entangled states. In addition to practical applications in quantum communication and quantum computation[16-20], teleportation provides a useful framework to study entanglement[21], especially in multipartite entanglement[22]. Recently, it has been attracting much interest to realize teleportation with genuine multipartite entanglement[22-25]. In Ref. [22] a scheme was proposed to teleport an arbitrary two-qubit state with a single four-qubit maximally entangled state. The idea was soon generalized to many-body systems[26-28] and demonstrated in an ion-trap system[29].

1 Probabilistic teleportation of an arbitrary two-particle entangled state

In this paper, we study a more general case

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Tel: 0746-6381254 Email: zf_80@126.com
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that the quantum channel is a four-qubit partially entangled state. This case should be much more practical than that of Ref. [22], because what the experimentally generated are generally partially entangled states or mixed states but not maximally entangled states. The quantum channel we used is a four-qubit linear cluster-class state[30]

$$|\Psi\rangle_{1234}=(c_0|0000\rangle+c_1|0011\rangle+c_2|1100\rangle-c_3|1111\rangle)_{1234} \quad (1)$$

where $\{c_i, i=0,1,2,3\}$ are normalized coefficients satisfying $\sum_{i=0}^{3}|c_i|^2=1$. Here we have considered the case that the phase difference between $c_j(j=0,1,2)$ and c_3 is less than π. Generally speaking, all the coefficients $\{|c_i|\}$ are different. Without losing generality, we assume that $|c_0|=\min\{|c_i|\}$. The cluster-class state in Eq. (1) is a generalization of the four-qubit cluster state $|C_4\rangle=(|0000\rangle+|0011\rangle+|1100\rangle-|1111\rangle)_{1234}/2$[5]. The unknown two-qubit state to be teleported can be written as

$$|\varphi\rangle_{t_1t_2}=(x_0|00\rangle+x_1|01\rangle+x_2|10\rangle+x_3|11\rangle)_{t_1t_2} \quad (2)$$

where $\sum_{i=0}^{3}|x_i|^2=1$, and $\{|00\rangle_{t_1t_2}, |01\rangle_{t_1t_2}, |10\rangle_{t_1t_2}, |11\rangle)_{t_1t_2}\}$ is the basis of an four-dimensional Hilbert space. Then the state of the total system is

$$\begin{aligned}|\Phi\rangle=|\varphi\rangle_{t_1t_2}\otimes|\Psi\rangle_{1234}=(&x_0c_0|000000\rangle+x_0c_1|000101\rangle+x_0c_2|001010\rangle-x_0c_3|001111\rangle+\\&x_1c_0|010000\rangle+x_1c_1|010101\rangle+x_1c_2|011010\rangle-x_1c_3|011111\rangle+x_2c_0|100000\rangle+x_2c_1|100101\rangle+\\&x_2c_2|101010\rangle-x_2c_3|101111\rangle+x_3c_0|110000\rangle+x_3c_1|110101\rangle+x_3c_2|111010\rangle-\\&x_3c_3|111111\rangle)_{t_1t_21324}\end{aligned} \quad (3)$$

We assume that Alice is the sender and holds particles 1, 3, t_1 and t_2, and Bob is the receiver holding particles 2 and 4. In the following, we will demonstrate explicitly the process of teleporting the state in Eq. (2) from Alice′s site to Bob′s site with a certain probability.

First Alice, performs particle pairs $(t_1,1)$ and $(t_2,3)$ a Bell-basis measurement respectively. The four Bell basis states are given by

$$|\Phi^{\pm}\rangle=\frac{1}{\sqrt{2}}(|00\rangle\pm|11\rangle),$$

$$|\Psi^{\pm}\rangle=\frac{1}{\sqrt{2}}(|10\rangle\pm|01\rangle) \quad (4)$$

There are 16 possible measurement outcomes, and the states of particles 2 and 4 collaps into one of following states

$$_{t_11}\langle\Phi^{\pm}|_{t_23}\langle\Phi^{\pm}|\Phi\rangle=\frac{1}{2}(x_0c_0|00\rangle+\pm x_1c_1|01\rangle\pm+x_2c_2|10\rangle\pm\mp x_3c_3|11\rangle)_{24} \quad (5)$$

$$_{t_11}\langle\Phi^{\pm}|_{t_23}\langle|\Psi^{\pm}|\Phi\rangle=\frac{1}{2}(x_0c_1|01\rangle+\pm x_1c_0|00\rangle\mp+x_2c_3|11\rangle\pm\pm x_3c_2|10\rangle)_{24} \quad (6)$$

$$_{t_11}\langle|\Psi^{\pm}|_{t_23}\langle\Phi^{\pm}|\Phi\rangle=\frac{1}{2}(\pm+x_0c_2|10\rangle\pm\mp x_1c_3|11\rangle++x_2c_0|00\rangle+\pm x_3c_1|01\rangle)_{24} \quad (7)$$

$$_{t_11}\langle|\Psi^{\pm}|_{t_23}\langle|\Psi^{\pm}|\Phi\rangle=\frac{1}{2}(\mp\pm x_0c_3|10\rangle\pm+x_1c_2|11\rangle+\pm x_2c_1|00\rangle++x_3c_0|01\rangle)_{24} \quad (8)$$

where all the states are unnormalized. In the above equations, the notes "±", "∓", or "+" before each coefficient from right to left correspond to the Bell-state measurement outcomes of particle pairs $(t_1,1)$ and $(t_2,3)$, respectively. Note that the total sign in front of each coefficient is determined by the number of "−". If the number of "−" is odd, the total sign is "−", otherwise, the total sign is "+". For example

$$_{t_11}\langle\Phi^-|_{t_23}\langle\Phi^+|\Phi\rangle=1/2(x_0c_0|00\rangle++x_1c_1|01\rangle-+x_2c_2|10\rangle--x_3c_3|11\rangle)_{24}=1/2(x_0c_0|00\rangle+x_1c_1|01\rangle-x_2c_2|10\rangle+x_3c_3|11\rangle)_{24} \quad (9)$$

Table 1 Bob′s single-particle rotations corresponding to Alice′s measurement results, and the related state of particles 2 and 4. I is identity operator and $\sigma^j(j=x,y,z)$ is usual Pauli matrix

Alice′s measurement result	Bob′s operation	The related state of particles 2 and 4
$_{t_11}\langle\Phi^+|_{t_23}\langle\Phi^+|\Phi\rangle$	$I_2\otimes I_4$	$|\psi^0\rangle_{24}$
$_{t_11}\langle\Phi^+|_{t_23}\langle\Phi^-|\Phi\rangle$	$I_2\otimes\sigma_4^z$	$|\psi^0\rangle_{24}$
$_{t_11}\langle\Phi^-|_{t_23}\langle\Phi^+|\Phi\rangle$	$\sigma_2^z\otimes I_4$	$|\psi^0\rangle_{24}$
$_{t_11}\langle\Phi^-|_{t_23}\langle\Phi^-|\Phi\rangle$	$\sigma_2^z\otimes\sigma_4^z$	$|\psi^0\rangle_{24}$
$_{t_11}\langle\Phi^+|_{t_23}\langle\Psi^+|\Phi\rangle$	$I_2\otimes\sigma_4^x$	$|\psi^1\rangle_{24}$
$_{t_11}\langle\Phi^+|_{t_23}\langle\Psi-|\Phi\rangle$	$I_2\otimes(-i\sigma_4^y)$	$|\psi^1\rangle_{24}$
$_{t_11}\langle\Phi^+|_{t_23}\langle\Psi^+|\Phi\rangle$	$\sigma_2^z\otimes\sigma_4^x$	$|\psi^1\rangle_{24}$
$_{t_11}\langle\Phi^-|_{t_23}\langle\Psi^-|\Phi\rangle$	$\sigma_2^z\otimes(-i\sigma_4^y)$	$|\psi^1\rangle_{24}$
$_{t_11}\langle\Psi^+|_{t_23}\langle\Phi^+|\Phi\rangle$	$\sigma_2^x\otimes I_4$	$|\psi^2\rangle_{24}$
$_{t_11}\langle\Psi^-|_{t_23}\langle\Phi^+|\Phi\rangle$	$(-i\sigma_2^y)\otimes I_4$	$|\psi^2\rangle_{24}$
$_{t_11}\langle\Psi^+|_{t_23}\langle\Phi^-|\Phi\rangle$	$\sigma_2^x\otimes\sigma_4^z$	$|\psi^2\rangle_{24}$
$_{t_11}\langle\Psi^-|_{t_23}\langle\Phi^-|\Phi\rangle$	$(-i\sigma_2^y)\otimes\sigma_4^z$	$|\psi^2\rangle_{24}$
$_{t_11}\langle\Psi^+|_{t_23}\langle\Psi^+|\Phi\rangle$	$\sigma_2^x\otimes\sigma_4^x$	$|\psi^3\rangle_{24}$
$_{t_11}\langle\Psi^+|_{t_23}\langle\Psi^-|\Phi\rangle$	$\sigma_2^x\otimes(-i\sigma_4^y)$	$|\psi^3\rangle_{24}$
$_{t_11}\langle\Psi^-|t_23\langle\Psi^+|\Phi\rangle$	$(-i\sigma_2^y)\otimes\sigma_4^x$	$|\psi^3\rangle_{24}$
$_{t_11}\langle\Psi^-|_{t_23}\langle\Psi^-|\Phi\rangle$	$(-i\sigma_2^y)\otimes(-i\sigma_4^y)$	$|\psi^3\rangle_{24}$

After the Bell-state measurements, Alice informs Bob of her measured results via a classical channel. Then Bob performs corresponding single-particle rotations on qubits 2 and 4 to establish a correspondence between x_i ($i=0,1,2,3$) and $|00\rangle_{24}$, $|01\rangle_{24}$, $|10\rangle_{24}$ and $|11\rangle_{24}$, shown in Eq. (2), respectively. Bob's operations against Alice's different measurement results and the related state of particles 2 and 4 are given in Table 1. The unnormalized states $\{|\psi^i\rangle_{24}, i=0,1,2,3\}$ in Table 1 are given by

$$|\psi^0\rangle_{24}=2^{-1}(x_0c_0|00\rangle+x_1c_1|01\rangle+x_2c_2|10\rangle-x_3c_3|11\rangle)_{24} \tag{10}$$

$$|\psi^1\rangle_{24}=2^{-1}(x_0c_1|00\rangle+x_1c_0|01\rangle-x_2c_3|10\rangle+x_3c_2|11\rangle)_{24} \tag{11}$$

$$|\psi^2\rangle_{24}=2^{-1}(x_0c_2|00\rangle-x_1c_3|01\rangle+x_2c_0|10\rangle+x_3c_1|11\rangle)_{24} \tag{12}$$

$$|\psi^3\rangle_{24}=2^{-1}(-x_0c_3|00\rangle+x_1c_2|01\rangle+x_2c_1|10\rangle+x_3c_0|11\rangle)_{24} \tag{13}$$

Now Bob introduces an auxiliary two-state particle A with the initial state $|0\rangle_A$ and performs a collective unitary transformation on particles 2, 4, and A. This operation depends on the state of particles 2 and 4 after Bob's single-particle rotations shown in Table 1. The corresponding unitary transformations for the states $\{|\psi^i\rangle_{24}, i=0,1,2,3\}$ are denoted by $\{U_i, i=0,1,2,3\}$, respectively. Under the basis

$\{|00\rangle_{24}|0\rangle_A, |01\rangle_{24}|0\rangle_A, |10\rangle_{24}|0\rangle_A, |11\rangle_{24}|0\rangle_A, |00\rangle_{24}|1\rangle_A, |01\rangle_{24}|1\rangle_A, |10\rangle_{24}|1\rangle_A, |11\rangle_{24}|1\rangle_A\}$

$\{U_i\}$ are 8×8 matrices given by

$$U_0=\begin{pmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & \frac{c_0}{c_1} & 0 & 0 & \sqrt{1-\left|\frac{c_0}{c_1}\right|^2} & 0 & 0 & 0\\
0 & 0 & \frac{c_0}{c_2} & 0 & 0 & \sqrt{1-\left|\frac{c_0}{c_2}\right|^2} & 0 & 0\\
0 & 0 & 0 & \frac{-c_0}{c_3} & 0 & 0 & \sqrt{1-\left|\frac{c_0}{c_3}\right|^2} & 0\\
0 & \sqrt{1-\left|\frac{c_0}{c_1}\right|^2} & 0 & 0 & \frac{-c_0^*}{c_1^*} & 0 & 0 & 0\\
0 & 0 & \sqrt{1-\left|\frac{c_0}{c_2}\right|^2} & 0 & 0 & \frac{-c_0^*}{c_2^*} & 0 & 0\\
0 & 0 & 0 & \sqrt{1-\left|\frac{c_0}{c_3}\right|^2} & 0 & 0 & \frac{c_0^*}{c_3^*} & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -1
\end{pmatrix} \tag{14}$$

$$U_1=\begin{pmatrix}
\frac{c_0}{c_1} & 0 & 0 & 0 & 0 & 0 & 0 & \sqrt{1-\left|\frac{c_0}{c_1}\right|^2}\\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & \frac{-c_0}{c_3} & 0 & 0 & \sqrt{1-\left|\frac{c_0}{c_3}\right|^2} & 0 & 0\\
0 & 0 & 0 & \frac{c_0}{c_2} & 0 & 0 & \sqrt{1-\left|\frac{c_0}{c_2}\right|^2} & 0\\
0 & 0 & 0 & 0 & -1 & 0 & 0 & 0\\
0 & 0 & \sqrt{1-\left|\frac{c_0}{c_3}\right|^2} & 0 & 0 & \frac{c_0^*}{c_3^*} & 0 & 0\\
0 & 0 & 0 & \sqrt{1-\left|\frac{c_0}{c_2}\right|^2} & 0 & 0 & \frac{-c_0^*}{c_2^*} & 0\\
\sqrt{1-\left|\frac{c_0}{c_1}\right|^2} & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-c_0^*}{c_1^*}
\end{pmatrix} \tag{15}$$

$$U_2=\begin{pmatrix} \frac{c_0}{c_2} & 0 & 0 & 0 & 0 & 0 & 0 & \sqrt{1-\left|\frac{c_0}{c_2}\right|^2} \\ 0 & \frac{-c_0}{c_3} & 0 & 0 & \sqrt{1-\left|\frac{c_0}{c_3}\right|^2} & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{c_0}{c_1} & 0 & 0 & \sqrt{1-\left|\frac{c_0}{c_1}\right|^2} & 0 \\ 0 & \sqrt{1-\left|\frac{c_0}{c_3}\right|^2} & 0 & 0 & \frac{c_0^*}{c_3^*} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & \sqrt{1-\left|\frac{c_0}{c_1}\right|^2} & 0 & 0 & \frac{-c_0^*}{c_1^*} & 0 \\ \sqrt{1-\left|\frac{c_0}{c_2}\right|^2} & 0 & 0 & 0 & 0 & 0 & 0 & \frac{-c_0^*}{c_2^*} \end{pmatrix} \tag{16}$$

$$U_3=\begin{pmatrix} \frac{-c_0}{c_3} & 0 & 0 & 0 & 0 & 0 & 0 & \sqrt{1-\left|\frac{c_0}{c_3}\right|^2} \\ 0 & \frac{c_0}{c_2} & 0 & 0 & \sqrt{1-\left|\frac{c_0}{c_2}\right|^2} & 0 & 0 & 0 \\ 0 & 0 & \frac{c_0}{c_1} & 0 & 0 & \sqrt{1-\left|\frac{c_0}{c_1}\right|^2} & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & \sqrt{1-\left|\frac{c_0}{c_2}\right|^2} & 0 & 0 & \frac{-c_0^*}{c_2^*} & 0 & 0 & 0 \\ 0 & 0 & \sqrt{1-\left|\frac{c_0}{c_1}\right|^2} & 0 & 0 & \frac{-c_0^*}{c_1^*} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ \sqrt{1-\left|\frac{c_0}{c_3}\right|^2} & 0 & 0 & 0 & 0 & 0 & 0 & \frac{c_0^*}{c_3^*} \end{pmatrix} \tag{17}$$

After the unitary transformation Bob measures the state of particle A. If the measured result is $|0\rangle_A$, the state $|\varphi\rangle_{24}$ can be obtained. Otherwise, the reconstruction of the original state in Eq. (2) fails. It can be easily verified that each of the states $\{|\psi^i\rangle_{24}, i=0,1,2,3\}$ contributes to $|c_0|^2/4$ success probability. For example, if Alice's measurement result is $_{t_1 1}\langle\Phi^+|_{t_2 3}\langle\Phi^+|\Phi\rangle$, the state of particles 2 and 4 is $|\psi^0\rangle_{24}$ after Bob performing corresponding single-particle rotations (see Table 1). The unitary transformation U_0 will transform the state $|\psi^0\rangle_{24}|0\rangle_A$ into

$$U_0|\psi^0\rangle_{24}|0\rangle_A=\frac{c_0}{2}|\varphi\rangle_{24}|0\rangle_A+\frac{1}{2}(x_1\sqrt{|c_1|^2-|c_0|^2}\cdot|0_2 0_4\rangle+x_2\sqrt{|c_2|^2-|c_0|^2}|0_2 1_4\rangle-x_3\sqrt{|c_3|^2-|c_0|^2}|1_2 0_4\rangle)|1\rangle_A \tag{18}$$

It is evident that there is $|c_0|^2/4$ probability to get the result $|0\rangle_A$ and obtain the state $|\varphi\rangle_{24}$. From Table 1 we can see that each of the states $\{|\psi^i\rangle_{24}, i=0,1,2,3\}$ corresponds to Alice's four possible measurement outcomes. So the total probability of successful teleportation is

$$p=4\times4\times|c_0|^2/4=4|c_0|^2 \tag{19}$$

Note that if $c_j=\min\{|c_i|, i=0,1,2,3\}(j=1,2,3)$ we can also construct appropriate unitary transformations and realize the teleportation with probability $p=4|c_j|^2$. As a result, the state $|\varphi\rangle$ in Eq. (2) can always be successfully teleported via the quantum channel in Eq. (1) with probability

$$p=4(\min\{|c_i|\})^2 \tag{20}$$

It can be seen that from Eq. (20) if $|c_i|=1/2$ the probability of successful teleportation $p=1$. That is to say, when the quantum channel is the four-qubit cluster state $|C_4\rangle$[5] the teleportation can be deterministically realized.

2 Conclusion

In conclusion, we studied the teleportation of an arbitrary two-qubit state with a single partially entangled state, a four-qubit cluster-class state in Eq. (1). This case is more practical than previous ones using maximally entangled states as the quantum channel. We demonstrated that the teleportation can be successfully realized with probability $p=4(\min\{|c_i|\})^2$ as long as Bob introduces an auxiliary two-state particle and performs an appropriate collective unitary transformation. Note that it is impossible to implement the above teleportation task with the well-know GHZ-class and W-class states. We also showed that when the quantum channel is a four-qubit cluster state (maximally entangled state), the teleportation can be definitly implemented. Imagining that if one can firstly obtain a four-qubit cluster state with probability p on Alice site and then use it as the quantum channel, teleportation can also be implemented with the same success probability as our scheme. Thus we can conclude that a four-qubit cluster state can be extracted from a single copy of the cluster-class state (1) with probability $4(\min\{|c_i|\})^2$ in principle. In the future, one can generalize our idea to the case where more than four particles are involved like the generalization of the scheme of Ref. [22]. This may open a new perspective for the applications of cluster-class states in quantum information processing.

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量子隐形传态的类簇态信道方案

钟 锋[1],于立志[2],李春树[1]
(1 湖南科技学院 物理系,湖南 永州 425100)
(2 阜阳师范学院 物理与电子科学学院,安徽 阜阳 236041)

摘 要:提出了利用一个四粒子类簇态来实现一个任意两粒子态的隐形传送方案.如果接受者能根据发送者提供的测量信息对量子态实施一个合适的幺正变换,那么隐形传送就能以一定的概率实现.由于该方案中充当量子信道的是部分纠缠态,因此该方案比以前基于最大纠缠态的方案更具有现实意义.同时研究导出一个重要的结论:可以从一个四粒子类簇态(部分纠缠态)中以一定的概率提取出一个四粒子簇态(最大纠缠态),这个概率等于成功隐形传态的概率.

关键词:量子光学;隐形传态;cluster 态;Bell 态测量;幺正变换

ZHONG Feng was born in 1980 and received his M. S. degree from Nanchang University in 2006. He is a lecturer at Hunan University of Science and Engineering and his major research interests focus on quantum optics.