A DETERMINISTIC SECURE QUANTUM COMMUNICATION PROTOCOL USING GENUINE FOUR-PARTICLE ENTANGLED STATES WITH INCOMPLETE QUANTUM TELEPORTATION*

Li Dong, Xiao-Ming Xiu†

Department of Physics, Bohai University
Jinzhou 121000, P.R. China

Yuan-Peng Ren

College of Applied Technology, Bohai University, Jinzhou 121000, P.R. China

Hui-Wei Liu

College of Information Science and Engineering
Bohai University, Jinzhou 121000, P.R. China

(Received February 8, 2010; revised version received April 30, 2010)

We propose a deterministic secure quantum communication protocol using genuine four-particle entangled states. With incomplete quantum teleportation, it reduces communication cost and needs no unitary operations to recover the original state.

PACS numbers: 03.67.Hk, 03.67.Dd, 03.65.Ud

1. Introduction

Quantum communication [1] is a charming art to transmit secret information between legitimate users. Using quantum no-cloning theorem and quantum correlation, the legitimate users can communicate with each other in security. Since the first quantum key distribution protocol was proposed by Bennett and Brassard in 1984 [2], many protocols concerning it have been presented [3–11].

* Supported by the National Natural Science Foundation of China under Grant No. 10704011 and the Research Project of the Education Department of Liaoning Province of China under Grant No. 2008006.

† Corresponding author xiuxiaomingdl@126.com

Different from quantum key distribution, quantum secure direct communication [12–19] and deterministic secure quantum communication [20–23] permit the communicators to transmit a bit of secret information without first establishing a key. In quantum secure direct communication, no classical bit is necessary in reading out secret information. An additional classical bit is required to read out secret information in deterministic secure quantum communication, as Long *et al.* [24] proposed, while the deterministic secure quantum communication protocols may be more secure in a noise channel and more convenient for quantum error correction.

In two-way communication protocols, it is necessary to send the particles carrying secret information in public channel. Therefore, for each block of transmission, an eavesdropping check is inevitable for secure communication. However, using quantum teleportation [25] which transmits the state of a quantum system from some place to other place without transmitting the object itself, no particle carrying secret information is transmitted and only the particles for sharing quantum channel are transmitted. So the security of communication bases on the security of the process for sharing the entangled state. As the particles are not exposed to the noise and the loss aroused by the quantum channel again, the bit generations rate and the security will increase in practical conditions [23, 24].

However, in the communication protocols using general quantum teleportation, some communications and operations are redundant. In this paper, an efficient deterministic secure quantum communication protocol using genuine four-particle entangled state is proposed. It is easy to implement and simpler than the ones using general quantum teleportation.

Next, we describe the deterministic secure quantum communication with the genuine four-particle entangled states in detail in Sec. 2. And then, we analyze security of the protocol in Sec. 3. The discussion and conclusion is presented in Sec. 4.

2. The deterministic secure quantum communication

The entanglement property of four-particle entangled state was studied by some researchers [26–30]. Thereinto, a genuine four-particle entangled state attracts some researchers' attention, which is different from the four-particle GHZ state under stochastic local operations and classical communication. With it, Yeo and Chua [30] proposed an explicit teleportation. Wang and Yang [31] presented a protocol for generating the state in an ion-trap system and showed that the sixteen states can be discriminated. Using the entangled state, Lin *et al.* [32] proposed a quantum secure direct communication using dense coding where a novel security test is adopted to ensure the security of communication. Applying entanglement swapping, Xiu *et al.* [33] proposed a deterministic secure quantum communication protocol. Qin *et al.* [34] shown that the protocol is insecure and Eve can distill a quarter of the secret information without detection, and proposed an improvement to resist the attack.

In this paper, an efficient deterministic secure quantum communication protocol with incomplete teleportation can be realized in security through the following two processes.

2.1. The process of sharing the genuine four-particle entangled state

The sharing of the genuine four-particle entangled state is crucial process in the quantum secure communication.

(1.1) Alice prepares particle sequence (A_1, A_2, B_1, B_2). Each group $(A_{1,i}, A_{2,i}, B_{1,i}, B_{2,i})$, $(i = 1, 2, \cdots, N)$ is in the genuine four-particle entangled state, which can be denoted as

$$\begin{aligned}
\left|\chi^{00}\right\rangle_{A_{1,i},A_{2,i},B_{1,i},B_{2,i}} &= \tfrac{1}{2\sqrt{2}}(|0000\rangle - |0011\rangle - |0101\rangle + |1001\rangle \\
&\quad + |0110\rangle + |1010\rangle + |1100\rangle + |1111\rangle)_{A_{1,i},A_{2,i},B_{1,i},B_{2,i}} \\
&= \tfrac{1}{2}(\left|\Phi_1^-\right\rangle|0+\rangle + \left|\Phi_1^+\right\rangle|0-\rangle \\
&\quad + \left|\Psi_1^-\right\rangle|1+\rangle + \left|\Psi_1^+\right\rangle|1-\rangle)_{A_{1,i},A_{2,i},B_{1,i},B_{2,i}} \\
&= \tfrac{1}{2}(\left|\Phi_2^+\right\rangle|+0\rangle + \left|\Phi_2^-\right\rangle|-0\rangle \\
&\quad - \left|\Psi_2^+\right\rangle|+1\rangle - \left|\Psi_2^-\right\rangle|-1\rangle)_{A_{1,i},A_{2,i},B_{1,i},B_{2,i}}\,. \qquad (1)
\end{aligned}$$

Here, $|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle), |-\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle); \left|\Phi_1^\pm\right\rangle = \frac{1}{\sqrt{2}}(|\phi^+\rangle \pm |\psi^-\rangle)$, $\left|\Psi_1^\pm\right\rangle = \frac{1}{\sqrt{2}}(|\psi^+\rangle \pm |\phi^-\rangle); \left|\Phi_2^\pm\right\rangle = \frac{1}{\sqrt{2}}(|\phi^+\rangle \pm |\psi^+\rangle), \left|\Psi_2^\pm\right\rangle = \frac{1}{\sqrt{2}}(|\psi^-\rangle \pm |\phi^-\rangle)$, where $|\phi^\pm\rangle = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle)$ and $|\psi^\pm\rangle = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle)$ are four two-particle Bell states.

Alice sends particles $(B_{1,i}, B_{2,i})$ as the transmitted block to Bob and remains particles $(A_{1,i}, A_{2,i})$ herself.

(1.2) After he received particles $(B_{1,i}, B_{2,i})$, Bob selects randomly a sufficiently large particle subset $(A_{1,c}, A_{2,c}, B_{1,c}, B_{2,c})$ as the checking group to check the security of quantum channel. The other particles are used to communicate between them. Here we adopt the security check method of quantum channel proposed by Lin *et al.* [32].

Bob performs measurements on particles $(B_{1,c}, B_{2,c})$ using the bases of $\{|0\rangle, |1\rangle\} \otimes \{|+\rangle, |-\rangle\}$ and $\{|+\rangle, |-\rangle\} \otimes \{|0\rangle, |1\rangle\}$ randomly, and then tells Alice which particles are selected as the checking group.

(1.3) Alice performs the measurements using the bases of $\{\left|\Phi_1^\pm\right\rangle, \left|\Psi_1^\pm\right\rangle\}$ and $\{\left|\Phi_2^\pm\right\rangle, \left|\Psi_2^\pm\right\rangle\}$ on particles $(A_{1,c}, A_{2,c})$. After that, they compare the measurement outcomes and analyze the security of quantum channel. If there is no eavesdropper, their measurement outcomes should comply with Eq. (1). If it accords perfectly, the sharing process of quantum channel succeeds. Otherwise, they discard the quantum channel and restart.

2.2. The process of deterministic secure quantum communication

Once the sharing process of the quantum channel is successfully completed, a deterministic secure quantum communication protocol using incomplete quantum teleportation can be realized in security.

(2.1) Ensuring the security of the quantum channel, they begin secure communication. Following the idea of teleportation, Alice prepares the encoded particle sequence $(a_{1,i}, a_{2,i})$ in the states $\{|0\rangle, |+\rangle\}$ ($\{|1\rangle, |-\rangle\}$) corresponding to the secret information 0(1).

(2.2) Alice performs measurements on particles $(a_{1,i}, a_{2,i}, A_{1,i}, A_{2,i})$ using the bases of $\left|\chi^{ij}\right\rangle = U^i \otimes U^j \left|\chi^{00}\right\rangle, (i, j = 0, 1, 2, 3)$, which can be obtained through performing unitary operations (U^i, U^j) on the former two particles in the state $\left|\chi^{00}\right\rangle$. The unitary operations can be denoted as $U^0 = I = |1\rangle\langle 1| + |0\rangle\langle 0|$, $U^1 = X = |1\rangle\langle 0| + |0\rangle\langle 1|$, $U^2 = Z = |0\rangle\langle 0| - |1\rangle\langle 1|$, and $U^3 = XZ = |1\rangle\langle 0| - |0\rangle\langle 1|$. After Alice's measurements, their states will collapse to one of the states $\left|\chi^{ij}\right\rangle$.

(2.3) Alice publicizes the information about encoded states and her measurement outcomes. If the states $\{|0\rangle, |1\rangle\}$ are used as the encoded state, Alice publicizes encoded state information 0, and if the states $\{|+\rangle, |-\rangle\}$ are used as the encoded state, the encoded state information is 1. At the same time, when the state $\{|0\rangle, |1\rangle\}$ is adopted to encode, Alice's measurement outcome and her measurement outcome information have the following correspondence, $\left|\chi^{ij}\right\rangle$ $i(j) = 0, 2 \to 0$ and $i(j) = 1, 3 \to 1$. When the state $\{|+\rangle, |-\rangle\}$ is adopted to encode, Alice's measurement outcome and Alice's measurement outcome information have the correspondence, $\left|\chi^{ij}\right\rangle$, $i(j) = 0, 1 \to 0$ and $\left|\chi^{ij}\right\rangle$, $i(j) = 2, 3 \to 1$.

(2.4) Bob performs the measurements on the particles in his side by using the bases of $\{|0\rangle, |1\rangle\}$ or $\{|+\rangle, |-\rangle\}$ according to Alice's encoded state information, 0 or 1. If his measurement outcome is $|0\rangle$ or $|+\rangle$, the recorded information is 0; if the measurement outcome is $|1\rangle$ or $|-\rangle$, the recorded information is 1. According to Alice's measurement outcome information, Bob can obtain Alice's secret information in terms of the addition of binary system. Explicitly, if Alice's measurement outcome information is 0, the corresponding bit of the recorded information is invariable, and if Alice's measurement outcome information is 1, the corresponding bit should be reversed in the recorded information ($0 \to 1$, or $1 \to 0$). Through this method, Bob can obtain Alice's secret information. The detailed process is also shown in Table I.

TABLE I

The detailed process that Bob obtains the secret information from Alice. Alice publicizes encoded state information (AESI) and measurement outcome information (AMOI) according to her encoded state (AES) and her measurement outcome (AMO) on particles $(a_{1,i}, a_{2,i}, A_{1,i}, A_{2,i})$ using the bases of $|\chi^{ij}\rangle$. After he received Alice's information, Bob performs $\{|0\rangle, |1\rangle\}$ or $\{|+\rangle, |-\rangle\}$ base measurement according to AESI, 0 or 1, and keeps his recorded information (BRI) by his measurement outcome (BMO). Finally, Bob can obtain Alice's secret information (ASI) based on the formula, ASI =BRI $\oplus$ AMOI, where '$\oplus$' denotes binary addition.

AES	AESI	AMO	AMOI	BMO	BRI	ASI
$\|0\rangle, \|1\rangle$	0	$\|\chi^{ij}\rangle, i(j) = 0, 2$	0	$\|0\rangle$	0	0
$\|0\rangle, \|1\rangle$	0	$\|\chi^{ij}\rangle, i(j) = 0, 2$	0	$\|1\rangle$	1	1
$\|0\rangle, \|1\rangle$	0	$\|\chi^{ij}\rangle, i(j) = 1, 3$	1	$\|0\rangle$	0	1
$\|0\rangle, \|1\rangle$	0	$\|\chi^{ij}\rangle, i(j) = 1, 3$	1	$\|1\rangle$	1	0
$\|+\rangle, \|-\rangle$	1	$\|\chi^{ij}\rangle, i(j) = 0, 1$	0	$\|+\rangle$	0	0
$\|+\rangle, \|-\rangle$	1	$\|\chi^{ij}\rangle, i(j) = 0, 1$	0	$\|-\rangle$	1	1
$\|+\rangle, \|-\rangle$	1	$\|\chi^{ij}\rangle, i(j) = 2, 3$	1	$\|+\rangle$	0	1
$\|+\rangle, \|-\rangle$	1	$\|\chi^{ij}\rangle, i(j) = 2, 3$	1	$\|-\rangle$	1	0

Evidently, Bob can also transmit the secret information to Alice using the similar method. It is no necessary that both states $|0\rangle, |1\rangle$ and $|+\rangle, |-\rangle$ are adopted simultaneously to encode. Alice only needs to select either one as the encoded state to realize the communication. Moreover, Alice need not send the encoded state information to Bob, so a lot of communication cost is reduced.

3. Security analysis of the deterministic secure quantum communication protocol

The crucial issue of quantum communication is its security and privacy. Because there is not transmission of the particle which carries the secret information, Trojan horse attacks [1, 35, 36] in optical implement cannot be performed. Next, we consider the entangle-measure attack. The entangle-measure attack was depicted in Ref. [32]. Here, we discuss it again.

Eve intercepts particles $(B_{1,i'}, B_{2,i'})$ and performs unitary operations on her auxiliary particles and the intercepted particles. It can make the auxiliary particles into entangled state. We can rewrite Eq. (1) as

$$\left|\chi^{00}\right\rangle_{A_{1,i},A_{2,i},B_{1,i},B_{2,i}} = \tfrac{1}{2}\left(\left|\phi^{+}\right\rangle|00\rangle - \left|\psi^{-}\right\rangle|01\rangle + \left|\psi^{+}\right\rangle|10\rangle - \left|\phi^{-}\right\rangle|11\rangle\right) . \tag{2}$$

After Eve's action, the whole state containing the particles of quantum channel and Eve's particles can be denoted as

$$\begin{aligned}
\left|\Psi'\right\rangle &= \tfrac{1}{2}[\left|\phi^{+}\right\rangle(|00,\epsilon_{00}\rangle+|01,\epsilon_{01}\rangle+|10,\epsilon_{02}\rangle+|11,\epsilon_{03}\rangle) \\
&\quad -\left|\psi^{-}\right\rangle(|00,\epsilon_{10}\rangle+|01,\epsilon_{11}\rangle+|10,\epsilon_{12}\rangle+|11,\epsilon_{13}\rangle) \\
&\quad +\left|\psi^{+}\right\rangle(|00,\epsilon_{20}\rangle+|01,\epsilon_{21}\rangle+|10,\epsilon_{22}\rangle+|11,\epsilon_{23}\rangle) \\
&\quad -\left|\phi^{-}\right\rangle(|00,\epsilon_{30}\rangle+|01,\epsilon_{31}\rangle+|10,\epsilon_{32}\rangle+|11,\epsilon_{33}\rangle)] \\
&= \tfrac{1}{2}(|v_1\rangle|0+\rangle+|v_2\rangle|0-\rangle+|v_3\rangle|1+\rangle+|v_4\rangle|1-\rangle) \\
&= \tfrac{1}{2}(|u_1\rangle|+0\rangle+|u_2\rangle|-0\rangle+|u_3\rangle|+1\rangle-|u_4\rangle|-1\rangle)\,, \qquad (3)
\end{aligned}$$

where

$$\begin{aligned}
|v_1\rangle &= \tfrac{1}{\sqrt{2}}[\left|\phi^{+}\right\rangle(|\epsilon_{00}\rangle+|\epsilon_{01}\rangle)-\left|\psi^{-}\right\rangle(|\epsilon_{10}\rangle+|\epsilon_{11}\rangle) \\
&\quad +\left|\psi^{+}\right\rangle(|\epsilon_{20}\rangle+|\epsilon_{21}\rangle)-\left|\phi^{-}\right\rangle(|\epsilon_{30}\rangle+|\epsilon_{31}\rangle)]\,, \\
|v_2\rangle &= \tfrac{1}{\sqrt{2}}[\left|\phi^{+}\right\rangle(|\epsilon_{00}\rangle-|\epsilon_{01}\rangle)-\left|\psi^{-}\right\rangle(|\epsilon_{10}\rangle-|\epsilon_{11}\rangle) \\
&\quad +\left|\psi^{+}\right\rangle(|\epsilon_{20}\rangle-|\epsilon_{21}\rangle)-\left|\phi^{-}\right\rangle(|\epsilon_{30}\rangle-|\epsilon_{31}\rangle)]\,, \\
|v_3\rangle &= \tfrac{1}{\sqrt{2}}[\left|\phi^{+}\right\rangle(|\epsilon_{02}\rangle+|\epsilon_{03}\rangle)-\left|\psi^{-}\right\rangle(|\epsilon_{12}\rangle+|\epsilon_{13}\rangle) \\
&\quad +\left|\psi^{+}\right\rangle(|\epsilon_{22}\rangle+|\epsilon_{23}\rangle)-\left|\phi^{-}\right\rangle(|\epsilon_{32}\rangle+|\epsilon_{33}\rangle)]\,, \\
|v_4\rangle &= \tfrac{1}{\sqrt{2}}[\left|\phi^{+}\right\rangle(|\epsilon_{02}\rangle-|\epsilon_{03}\rangle)-\left|\psi^{-}\right\rangle(|\epsilon_{12}\rangle-|\epsilon_{13}\rangle) \\
&\quad +\left|\psi^{+}\right\rangle(|\epsilon_{22}\rangle-|\epsilon_{23}\rangle)-\left|\phi^{-}\right\rangle(|\epsilon_{32}\rangle-|\epsilon_{33}\rangle)]\,, \\
|u_1\rangle &= \tfrac{1}{\sqrt{2}}[\left|\phi^{+}\right\rangle(|\epsilon_{00}\rangle+|\epsilon_{02}\rangle)-\left|\psi^{-}\right\rangle(|\epsilon_{10}\rangle+|\epsilon_{12}\rangle) \\
&\quad +\left|\psi^{+}\right\rangle(|\epsilon_{20}\rangle+|\epsilon_{22}\rangle)-\left|\phi^{-}\right\rangle(|\epsilon_{30}\rangle+|\epsilon_{32}\rangle)]\,, \\
|u_2\rangle &= \tfrac{1}{\sqrt{2}}[\left|\phi^{+}\right\rangle(|\epsilon_{00}\rangle-|\epsilon_{02}\rangle)-\left|\psi^{-}\right\rangle(|\epsilon_{10}\rangle-|\epsilon_{12}\rangle) \\
&\quad +\left|\psi^{+}\right\rangle(|\epsilon_{20}\rangle-|\epsilon_{22}\rangle)-\left|\phi^{-}\right\rangle(|\epsilon_{30}\rangle-|\epsilon_{32}\rangle)]\,, \\
|u_3\rangle &= \tfrac{1}{\sqrt{2}}[\left|\phi^{+}\right\rangle(|\epsilon_{01}\rangle+|\epsilon_{03}\rangle)-\left|\psi^{-}\right\rangle(|\epsilon_{11}\rangle+|\epsilon_{13}\rangle) \\
&\quad +\left|\psi^{+}\right\rangle(|\epsilon_{21}\rangle+|\epsilon_{23}\rangle)-\left|\phi^{-}\right\rangle(|\epsilon_{31}\rangle+|\epsilon_{33}\rangle)]\,, \\
|u_4\rangle &= \tfrac{1}{\sqrt{2}}[\left|\phi^{+}\right\rangle(|\epsilon_{01}\rangle-|\epsilon_{03}\rangle)-\left|\psi^{-}\right\rangle(|\epsilon_{11}\rangle-|\epsilon_{13}\rangle) \\
&\quad +\left|\psi^{+}\right\rangle(|\epsilon_{21}\rangle-|\epsilon_{23}\rangle)-\left|\phi^{-}\right\rangle(|\epsilon_{31}\rangle-|\epsilon_{33}\rangle)]\,. \qquad (4)
\end{aligned}$$

Comparing Eq. (4) with Eq. (1), if Eve does not want to be found in the process of security check in bases of $\{\left|\Phi_1^{\pm}\right\rangle,\left|\Psi_1^{\pm}\right\rangle\}\otimes\{|0\rangle,|1\rangle\}\otimes\{|+\rangle,|-\rangle\}$, it must be satisfied that

$$\begin{aligned}
|\epsilon_{00}\rangle &= |\epsilon_{11}\rangle\,, \quad |\epsilon_{22}\rangle=|\epsilon_{33}\rangle\,, \quad |\epsilon_{01}\rangle=|\epsilon_{10}\rangle\,, \quad |\epsilon_{23}\rangle=|\epsilon_{32}\rangle\,, \\
|\epsilon_{20}\rangle &= |\epsilon_{21}\rangle=|\epsilon_{30}\rangle=|\epsilon_{31}\rangle=0\,, \quad |\epsilon_{02}\rangle=|\epsilon_{03}\rangle=|\epsilon_{12}\rangle=|\epsilon_{13}\rangle\,. \qquad (5)
\end{aligned}$$

Similarly, when Alice and Bob check the security of the process of distribution using the bases of $\{\left|\Phi_2^{\pm}\right\rangle, \left|\Psi_2^{\pm}\right\rangle\} \otimes \{|+\rangle, |-\rangle\} \otimes \{|0\rangle, |1\rangle\}$, Eve's action cannot be found if it is satisfied that

$$\begin{aligned} |\epsilon_{00}\rangle &= |\epsilon_{22}\rangle\,, \qquad |\epsilon_{11}\rangle = |\epsilon_{33}\rangle\,, \qquad |\epsilon_{02}\rangle = |\epsilon_{20}\rangle\,, \qquad |\epsilon_{13}\rangle = |\epsilon_{31}\rangle\,, \\ |\epsilon_{10}\rangle &= |\epsilon_{12}\rangle = |\epsilon_{30}\rangle = |\epsilon_{32}\rangle = 0\,, \qquad |\epsilon_{01}\rangle = |\epsilon_{03}\rangle = |\epsilon_{21}\rangle = |\epsilon_{23}\rangle\,. \end{aligned} \tag{6}$$

According to Eq. (3), Eq. (5) and Eq. (6), it can be deduced

$$\begin{aligned} \left|\chi^{00\prime}\right\rangle &= \tfrac{1}{2}\left(\left|\phi^{+}\right\rangle|00,\epsilon_{00}\rangle - \left|\psi^{-}\right\rangle|01,\epsilon_{00}\rangle + \left|\psi^{+}\right\rangle|10,\epsilon_{00}\rangle - \left|\phi^{-}\right\rangle|11,\epsilon_{00}\rangle\right) \\ &= \left|\chi^{00}\right\rangle|\epsilon_{00}\rangle\,. \end{aligned} \tag{7}$$

That is, Eve's auxiliary particles are not entangled into the four-particle entangled state. So Eve cannot steal secret information if she does not want to be found.

4. Discussion and conclusion

Using the idea of incomplete quantum teleportation, we propose a deterministic secure quantum communication protocol. In two-way communication protocols where the particles carrying secret information must be sent in a public channel, Eve can make interruption of communication by intercepting these particles, although she would not obtain any information in some cases. However, in our protocol, the idea of quantum teleportation is used to transmit the secret information. Eve has no access to the encoded particles in Alice's site. After the sharing of the entangled states, there is no way to obtain the secret information for her. Thus the protocol is secure once the security check is passed.

For transmitting one qubit, Alice needs to send Bob two classical bits of information in general quantum teleportation. In our protocol, it needs Alice to send one classical-bit information for one-bit secret information, so it can reduce one classical-bit information from Alice to Bob. Using a four-particle entangled state, two-bit information can be transmitted between Alice and Bob, which is equal to that of the protocol using general quantum teleportation. That is to say, transmission of two bit information needs two-bit classical information and one genuine four-particle entangled state. When the particles for checking security of quantum channel are not taken into account, the transmission efficiency is $\eta = 100\%$ like all teleportation schemes, because no genuine four-particle entangled state needs to be discarded. On the other hand, in a general one, after Bob receives Alice's measurement outcome, he performs a unitary operation on his particle to transform it to the desired state. Whereas, in our protocol, the unitary operation to recover the original state is not necessary, so the presented protocol can save a lot of cost consumption.

To sum up, with incomplete quantum teleportation, we propose a deterministic secure quantum communication protocol. It consumes lesser cost than the protocols of general quantum teleportation. We expect that it can be realized in the near future since many quantum teleportation protocol have been realized in experiment of photons and atoms [37, 38].

REFERENCES

[1] N. Gisin, G. Ribordy, W. Tittel, H. Zbinden, *Rev. Mod. Phys.* **74**, 145 (2002).

[2] C.H. Bennett, G. Brassard, in *Proceedings of IEEE International Conference on Computer, Systems and Signal Processing, Bangalore, India*, IEEE, New York 1984, p. 175.

[3] A.K. Ekert, *Phys. Rev. Lett.* **67**, 661 (1991).

[4] C.H. Bennett, G. Brassard, N.D. Mermin, *Phys. Rev. Lett.* **68**, 557 (1992).

[5] D. Bruss, *Phys. Rev. Lett.* **81**, 3018 (1998).

[6] P. Xue, C.F. Li, G.C. Guo, *Phys. Rev.* **A65**, 022317 (2002).

[7] A. Acín, N. Gisin, L. Masanes, *Phys. Rev. Lett.* **97**, 120405 (2006).

[8] H. Lv, A.X. Chen, X.D. Yan, *Chin. Phys. B* **16**, 2862 (2007).

[9] H. Wen , Z.F. Han, G.C. Guo, P.L. Hong, *Chin. Phys. B* **18**, 435 (2009).

[10] X.M. Xiu, L. Dong, Y.J. Gao, F. Chi, *Opt. Commun.* **282**, 4171 (2009).

[11] G.L. Long, X.S. Liu, *Phys. Rev.* **A65**, 032302 (2002).

[12] K. Boström, T. Felbinger, *Phys. Rev. Lett.* **89**, 187902 (2002).

[13] F.G. Deng, G.L. Long, X.S. Liu, *Phys. Rev.* **A68**, 042317 (2003).

[14] F.G. Deng, G.L. Long, *Phys. Rev.* **A69**, 052319 (2004).

[15] C. Wang, F.G. Deng, Y.S. Li, X.S. Liu, G.L. Long, *Phys. Rev.* **A71**, 044305 (2005).

[16] F.G. Deng, X.H. Li, C.Y. Li, P. Zhou, H.Y. Zhou, *Phys. Lett.* **A359**, 359 (2006).

[17] C. Wang, F.G. Deng, G.L. Long, *Opt. Commun.* **253**, 15 (2005).

[18] F.G. Deng, X.H. Li, C.Y. Li, P. Zhou, H.Y. Zhou, *Chin. Phys.* **16**, 3553 (2007).

[19] X.L. Zhang, Y.X. Zhang, H. Wei, *Chin. Phys. B* **18**, 435 (2009).

[20] K. Shimizu, N. Imoto, *Phys. Rev.* **A60**, 157 (1999).

[21] A. Beige, B.G. Englert, C. Kurtsiefer, H. Weinfurter, *Acta. Phys. Pol. A* **101**, 357 (2002).

[22] H. Lee, J. Lim, H.J. Yang, *Phys. Rev.* **A73**, 042305 (2006); Z.J. Zhang, J. Liu, D. Wang, S.H. Shi, *Phys. Rev.* **A75**, 026301 (2007).

[23] F.L. Yan, X.Q. Zhang, *Euro. Phys. J.* **B41**, 75 (2004).

[24] G.L. Long, F.G. Deng, C. Wang, X.H. Li, K. Wen, W.Y. Wang, *Front. Phys. China* **2**, 251 (2007).

[25] C.H. Bennett, G. Brassard, C. Crepeau, R. Jozsa, A. Peres, W.K. Wootters, *Phys. Rev. Lett.* **70**, 1895 (1993); L. Vaidman, *Phys. Rev.* **A49**, 1473 (1994); G. Brassard, S. Braunstein, R. Cleve, *Physica D* **120**, 43 (1998); G. Rigolin, *Phys. Rev.* **A71**, 032303 (2005).

[26] F. Verstraete, J. Dehaene, B. De Moor, H. Verschelde, *Phys. Rev.* **A65**, (2002) 052112.

[27] J. Lee, H. Min, S.D. Oh, *Phys. Rev.* **A66**, 052318 (2002).

[28] A. Osterloh, J. Siewert, *Phys. Rev.* **A72**, 012337 (2005).

[29] Y.K. Bai, D. Yang, Z.D. Wang, *Phys. Rev.* **A76**, 022336 (2007); Y.K. Bai, Z.D. Wang, *Phys. Rev.* **A77**, 032313 (2008).

[30] Y. Yeo, W.K. Chua, *Phys. Rev. Lett.* **96**, 060502 (2006).

[31] X.W. Wang, G.J. Yang, *Phys. Rev.* **A78**, 024301 (2008).

[32] S. Lin, Q.Y. Wen, F. Gao, F.C. Zhu, *Phys. Rev.* **A78**, 064304(2008).

[33] X.M. Xiu, H.K. Dong, L. Dong, Y.J. Gao, F. Chi, *Opt. Commun.* **282**, 2457 (2009).

[34] S.J. Qin, Q.Y. Wen, L.M. Meng, F.C. Zhu, S. Lin, F.Z. Guo, F.C. Zhu, *Opt. Commun.* **282**, (2009) 4017.

[35] Q.Y. Cai, *Phys. Lett.* **A351**, 23 (2006).

[36] F.G. Deng, P. Zhou, X.H. Li, C.Y. Li, H.Y. Zhou, `quant-ph/0508168`.

[37] D. Bouwmeester, J.W. Pan, K. Mattle, M. Eibl, H. Weinfurter, A. Zeilinger, *Nature* **390**, 575 (1997); D. Boschi, S. Branca, F. De Martini, L. Hardy, S. Popescu, *Phys. Rev. Lett.* **80**, 1121 (1998); I. Marcikic, H. d. Riedmatten, W. Tittel, H. Zbinden, N. Gisin, *Nature* **421**, 509 (2003); R. Ursin *et al.*, *Nature* **430**, 849 (2004).

[38] M. Riebe, H. Häfner, C.F. Roos, W. Hänsel, M. Ruth, J. Benhelm, G.P.T. Lancaster, T.W. Körber, C. Becher, F. Schmidt-Kaler, D.F.V. James, R. Blatt, *Nature* **429**, 734 (2004); M.D. Barrett, J. Chiaverini, T. Schaetz, J. Britton, W.M. Itano, J.D. Jost, E. Knill, C. Langer, D. Leibfried, R. Ozeri, D.J. Wineland, *Nature* **429**, 737 (2004); S. Olmschenk, D.N. Matsukevich, P. Maunz, D. Hayes, L.M. Duan, C. Monroe, *Science* **323**, 486 (2009).