文章编号:1004-4213(2010)09-1627-4

利用两个 EPR 态完全隐形传输四粒子 W 态*

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摘　要:为了减少量子隐形传态中的测量次数和运算量,提出了一个利用两个 EPR 对作为量子信道,实现四粒子 W 纠缠态的隐形传输的方案.发送者 Alice 只需利用 16 个正交完备测量基对要传送的未知四粒子纠缠 W 态和两个 EPR 对中属于自己的粒子做一次正交完备基测量,然后将测量所产生的 16 种塌陷态结果通过经典信道告知接收者,接收者 Bob 根据这些信息,通过引入两个辅助粒子 B_3B_4,并对手中拥有的粒子做适当的 Toffoli 门、C-Not 门、Pauli-X 门、Pauli-Z 门变换,就能将 16 种畸变态全部恢复到发送者 Alice 欲传送的未知四粒子原始量子态,从而以 100%的概率实现四粒子纠缠 W 态的隐形传输.利用量子力学波函数的叠加原理和变换算符的思想,很容易得出正交完备基测量后的 16 种塌陷态表达式和接收者 Bob 所做的由量子门组成的幺正变换的表达式.该方案中由于采用了正交完备基测量的方法,大大减少了发送者所需要做的测量计算,而且整个方案只需要一次正交完备基测量和由各种量子逻辑门组成的简单幺正变换,实现更为容易.

关键词:隐形传态;正交完备测量基;四粒子 W 态

中图分类号:O431　　**文献标识码**:A　　**doi**:10.3788/gzxb20103909.1627

0　引言

自 Bennet 等人[1]提出量子态传输的思想之后,量子态的隐形传输就成了量子信息领域最重要的研究对象之一,在近几年得到迅速而广泛的推广[2-5].郑亦庄[6]等提出利用三个二粒子纠缠态作为量子信道,实现三粒子纠缠 W 态的隐形传态的方案;张国华[7]等提出利用两个二粒子部分纠缠态作为量子信道,实现四粒子纠缠态的概率隐形传输方案;闫丽华[8]等提出利用两个 EPR 态作为量子信道隐形传送任意三原子 W 的方案;刘敏[9]等给出了利用四个 Bell 对纠缠通道来传送四粒子纠缠 W 态的方案.但在这些传案中,发送者欲传送未知的量子态,需要进行 Bell 基测量、Handamard 变换、Von-Neuman 测量等.

本文提出利用两个 EPR 对作为量子信道,实现四粒子 W 纠缠态的隐形传输的方案.由量子力学波函数的叠加特性及算符变换出发[10-11],将量子隐形态的体系的总量子态按正交完备基展开,接受者通过引入辅助粒子,然后对自己拥有的粒子进行相应的变换,就可使粒子处于待发送的原始量子态.

* 陕西省自然科学基金(2009JM1007)资助
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收稿日期:2010-01-21　　修回日期:2010-05-06

1　四粒子 W 量子态的隐形传送

假设发送者 Alice 想要传送一个由粒子 a_1、a_2、a_3、a_4 组成的未知四粒子纠缠 W 态

$$|w\rangle_{a_1a_2a_3a_4}=(\alpha|0001\rangle+\beta|0010\rangle+\gamma|0100\rangle+\delta|1000\rangle)_{a_1a_2a_3a_4} \quad (1)$$

给接受者 Bob,其中 $\alpha^2+\beta^2+\gamma^2+\delta^2=1$.为将未知的量子态 $|w\rangle_{a_1a_2a_3a_4}$ 传送给遥远的接收者 Bob ,发送者 Alice 和接受者 Bob 之间假设建立两个 EPR 对作为量子通道[12-13].

$$|\varphi\rangle_{A_1B_1}=1/2^{1/2}(|00\rangle+|11\rangle)_{A_1B_1} \quad (2)$$

$$|\varphi\rangle_{A_2B_2}=1/2^{1/2}(|00\rangle+(11\rangle)_{A_2B_2} \quad (3)$$

假设 Alice(发送方)拥有粒子 a_1、a_2、a_3、a_4 和粒子(A_1,A_2),Bob 拥有粒子(B_1,B_2),则总的量子态为

$$|\psi\rangle_s=|\chi\rangle_{a_1a_2a_3a_4}\otimes|\varphi\rangle_{A_1B_1}\otimes|\varphi\rangle_{A_2B_2}= 1/2(\alpha|00010000\rangle+\alpha|00010011\rangle+\alpha00011100\rangle+\alpha|00011111\rangle+\beta|00100000\rangle+\beta|00100011\rangle+\beta|00101100\rangle+\beta|00101111\rangle+\gamma|0100000\rangle+\gamma|01000011\rangle+\gamma|01001100\rangle+\gamma|01001111\rangle+\delta|10000000\rangle+\delta|10000011\rangle+\delta|10001100\rangle+\delta|10001111\rangle)_{a_1a_2a_3a_4A_1B_1A_2B_2} \quad (4)$$

接着,Alice 对手中的粒子 a_1、a_2、a_3、a_4、A_1、A_2 进行正交完备基测量,其测量基为

$$|\varphi^1\rangle=1/2(|000100\rangle+|001001\rangle+|010010\rangle+|100011\rangle)_{a_1a_2a_3a_4A_1A_2} \quad (5.1)$$

$$|\varphi^2\rangle=1/2(|000100\rangle+|001001\rangle-|010010\rangle-$$

$$|100011\rangle)_{a_1a_2a_3a_4A_1A_2} \quad (5.2)$$

$$|\varphi^3\rangle=1/2(|000110\rangle+|001011\rangle+|010000\rangle+|100001\rangle)_{a_1a_2a_3a_4A_1A_2} \quad (5.3)$$

$$|\varphi^4\rangle=1/2(|000110\rangle+|001011\rangle-|010000\rangle-|100001\rangle)_{a_1a_2a_3a_4A_1A_2} \quad (5.4)$$

$$|\varphi^5\rangle=1/2(|000100\rangle-|001001\rangle+|010010\rangle+|100011\rangle)_{a_1a_2a_3a_4A_1A_2} \quad (5.5)$$

$$|\varphi^6\rangle=1/2(|000100\rangle-|001001\rangle-|010010\rangle+|100011\rangle)_{a_1a_2a_3a_4A_1A_2} \quad (5.6)$$

$$|\varphi^7\rangle=1/2(|000110\rangle-|001011\rangle+|010000\rangle-|100001\rangle)_{a_1a_2a_3a_4A_1A_2} \quad (5.7)$$

$$|\varphi^8\rangle=1/2(|000110\rangle-|001011\rangle-|010000\rangle+|100001\rangle)_{a_1a_2a_3a_4A_1A_2} \quad (5.8)$$

$$|\varphi^9\rangle=1/2(|000101\rangle+|001000\rangle+|010011\rangle+|100010\rangle)_{a_1a_2a_3a_4A_1A_2} \quad (5.9)$$

$$|\varphi^{10}\rangle=1/2(|000101\rangle+|001000\rangle-|010011\rangle-|100010\rangle)_{a_1a_2a_3a_4A_1A_2} \quad (5.10)$$

$$|\varphi^{11}\rangle=1/2(|000111\rangle+|001010\rangle+|010001\rangle+|100000\rangle)_{a_1a_2a_3a_4A_1A_2} \quad (5.11)$$

$$|\varphi^{12}\rangle=1/2(|000111\rangle+|001010\rangle-|010001\rangle-|100000\rangle)_{a_1a_2a_3a_4A_1A_2} \quad (5.12)$$

$$|\varphi^{13}\rangle=1/2(|000101\rangle-|001000\rangle+|010011\rangle-|100010\rangle)_{a_1a_2a_3a_4A_1A_2} \quad (5.13)$$

$$|\varphi^{14}\rangle=1/2(|000101\rangle-|001000\rangle-|010011\rangle+|100010\rangle)_{a_1a_2a_3a_4A_1A_2} \quad (5.14)$$

$$|\varphi^{15}\rangle=1/2(|000111\rangle-|001010\rangle+|010001\rangle-|100000\rangle)_{a_1a_2a_3a_4A_1A_2} \quad (5.15)$$

$$|\varphi^{16}\rangle=-1/2(|000111\rangle-|001010\rangle-|010001\rangle+|100000\rangle)_{a_1a_2a_3a_4A_1A_2} \quad (5.16)$$

测量后粒子 B_1、B_2 塌陷至 16 种可能形式

$$|\psi^1\rangle_{B_1B_2}=\langle\varphi^1|\psi\rangle_s=1/4(\alpha|00\rangle+\beta|01\rangle+\gamma|10\rangle+\delta|11\rangle)_{B_1B_2} \quad (6.1)$$

$$|\psi^2\rangle_{B_1B_2}=1/4(\alpha|00\rangle+\beta|01\rangle-\gamma|10\rangle-\delta|11\rangle)_{B_1B_2} \quad (6.2)$$

$$|\psi^3\rangle_{B_1B_2}=1/4(\alpha|10\rangle+\beta|11\rangle+\gamma|00\rangle+\delta|01\rangle)_{B_1B_2} \quad (6.3)$$

$$|\psi^4\rangle_{B_1B_2}=1/4(\alpha|10\rangle+\beta|11\rangle-\gamma|00\rangle-\delta|01\rangle)_{B_1B_2} \quad (6.4)$$

$$|\psi^5\rangle_{B_1B_2}=1/4(\alpha|00\rangle-\beta|01\rangle+\gamma|10\rangle-\delta|11\rangle)_{B_1B_2} \quad (6.5)$$

$$|\psi^6\rangle_{B_1B_2}=1/4(\alpha|00\rangle-\beta|01\rangle-\gamma|10\rangle+\delta|11\rangle)_{B_1B_2} \quad (6.6)$$

$$|\psi^7\rangle_{B_1B_2}=1/4(\alpha|10\rangle-\beta|11\rangle+\gamma|00\rangle-\delta|01\rangle)_{B_1B_2} \quad (6.7)$$

$$|\psi^8\rangle_{B_1B_2}=1/4(\alpha|10\rangle+\beta|11\rangle-\gamma|00\rangle+\delta|01\rangle)_{B_1B_2} \quad (6.8)$$

$$|\psi^9\rangle_{B_1B_2}=1/4(\alpha|01\rangle+\beta|00\rangle+\gamma|11\rangle+\delta|10\rangle)_{B_1B_2} \quad (6.9)$$

$$|\psi^{10}\rangle_{B_1B_2}=1/4(\alpha|01\rangle+\beta|00\rangle-\gamma|11\rangle-\delta|10\rangle)_{B_1B_2} \quad (6.10)$$

$$|\psi^{11}\rangle_{B_1B_2}=1/4(\alpha|11\rangle+\beta|10\rangle+\gamma|01\rangle+\delta|00\rangle)_{B_1B_2} \quad (6.11)$$

$$|\psi^{12}\rangle_{B_1B_2}=1/4(\alpha|11\rangle+\beta|10\rangle-\gamma|01\rangle-\delta|00\rangle)_{B_1B_2} \quad (6.12)$$

$$|\psi^{13}\rangle_{B_1B_2}=1/4(\alpha|01\rangle-\beta|00\rangle+\gamma|11\rangle-\delta|10\rangle)_{B_1B_2} \quad (6.13)$$

$$|\psi^{14}\rangle_{B_1B_2}=1/4(\alpha|01\rangle-\beta|00\rangle-\gamma|11\rangle+\delta|10\rangle)_{B_1B_2} \quad (6.14)$$

$$|\psi^{15}\rangle_{B_1B_2}=1/4(\alpha|11\rangle-\beta|10\rangle+\gamma|01\rangle-\delta|00\rangle)_{B_1B_2} \quad (6.15)$$

$$|\psi^{16}\rangle_{B_1B_2}=1/4(\alpha|11\rangle-\beta|10\rangle-\gamma|01\rangle+\delta|00\rangle)_{B_1B_2} \quad (6.16)$$

接收方 Bob 在接受到由发送方 Alice 通过经典信道传送过来的测量结果后，这时测量结果已经发生畸变，为了成功得到 Alice 所要传送的未知量子态，Bob 需要引入辅助粒子 $|00\rangle B_3B_4$，对完备基测量以后的塌陷态进行幺正变换，从而实现对畸变态的恢复，例如：当测量基为 $|\varphi^1\rangle$ 时，其塌陷态为，Bob 引入辅助粒子 $|00\rangle B_3B_4$ 后，其态为

$$|\psi^1\rangle_{B_1B_2}|00\rangle_{B_3B_4}=1/4(\alpha|0000\rangle+\beta|0100\rangle+\gamma|1000\rangle+\delta|1100\rangle)_{B_1B_2B_3B_4}$$

Bob 首先对粒子 B_4 进行(σ_x)操作得

$$|\psi^1\rangle_{B_1B_2}|00\rangle_{B_3B_4}=1/4(\alpha|0001\rangle+\beta|0101\rangle+\gamma|1001\rangle+\delta|1101\rangle)_{B_1B_2B_3B_4}$$

接着 Bob 以 B_2 为控制位 B_3 为靶位进行 Controlled-NOT(U_{C-NOT})门操作，得

$$|\psi^1\rangle_{B_1B_2}|00\rangle_{B_3B_4}=1/4(\alpha|0001\rangle+\beta|0111\rangle+\gamma|1001\rangle+\delta|1111\rangle)_{B_1B_2B_3B_4}$$

同上，Bob 接着进行了以 B_3 为控制位 B_2 和 B_4 分别为靶位的 U_{C-NOT} 门操作以及以 B_1 为控制位 B_3 为靶位的 U_{C-NOT} 门操作后得

$$|\psi^1\rangle_{B_1B_2}|00\rangle_{B_3B_4}=1/4(\alpha|0001\rangle+\beta|0010\rangle+\gamma|1011\rangle+\delta|1000\rangle)_{B_1B_2B_3B_4}$$

然后 Bob 对粒子 B_2、B_3、B_4 进行以 B_3B_4 为控制位 B_2 为靶位的 Toffoli(T)门变换，得

$$|\psi^1\rangle_{B_1B_2}|00\rangle_{B_3B_4}=1/4(\alpha|0001\rangle+\beta|0010\rangle+\gamma|1111\rangle+\delta|1000\rangle)_{B_1B_2B_3B_4}$$

最后 Bob 对粒子 B_2、B_3、B_4 分别进行以 B_2 为控制位，B_3、B_4 分别为靶位的 U_{C-NOT} 门操作后得

$$|\psi^1\rangle_{B_1B_2}|00\rangle_{B_3B_4}=1/4(\alpha|0001\rangle+\beta|0010\rangle+$$

$\gamma|0100\rangle+\delta|1000\rangle)_{B_1B_2B_3B_4}$

设上述所有的变换用 U 表示. 可以看到，在 Bob 做完上述幺正变换后，畸变态即可恢复到 Alice 欲传送的原始量子态，即量子隐形传态成功. 其余 15 种量子态情况也可用类似方法进行，对应表 1.

表 1　各塌陷态及其对应的幺正变换

Table 1　Each collapse state and the corresponding unitary transformation

Collapse state	The corresponding unitary transformation
$\|\Psi^1\rangle_{B_1B_2}\|00\rangle_{B_3B_4}$	$(\sigma_x)_{B_4}(U_{\mathrm{C-NOT}})_{B_2B_3}(U_{\mathrm{C-NOT}})_{B_3B_2}(U_{\mathrm{C-NOT}})_{B_3B_4}(U_{\mathrm{C-NOT}})_{B_1B_3}$ $\mathrm{T}B_3B_4,B_2(U_{\mathrm{C-NOT}})_{B_2B_1}(U_{\mathrm{C-NOT}})_{B_2B_3}(U_{\mathrm{C-NOT}})_{B_2B_4}$
$\|\Psi^2\rangle_{B_1B_2}\|00\rangle_{B_3B_4}$	$U(\sigma_z)_{B_1}(\sigma_z)_{B_2}$
$\|\Psi^3\rangle_{B_1B_2}\|00\rangle_{B_3B_4}$	$U(\sigma_x)_{B_2}(\sigma_x)_{B_4}\mathrm{T}B_1B_2,B_3(U_{\mathrm{C-NOT}})_{B_3B_1}(U_{\mathrm{C-NOT}})_{B_3B_2}$ $(U_{\mathrm{C-NOT}})_{B_3B_4}(U_{\mathrm{C-NOT}})_{B_1B_3}$
$\|\Psi^4\rangle_{B_1B_2}\|00\rangle_{B_3B_4}$	$U(\sigma_x)_{B_2}(\sigma_x)_{B_4}\mathrm{T}B_1B_2,B_3(U_{\mathrm{C-NOT}})_{B_3B_1}(U_{\mathrm{C-NOT}})_{B_3B_2}$ $(U_{\mathrm{C-NOT}})_{B_3B_4}(U_{\mathrm{C-NOT}})_{B_1B_3}(\sigma_z)_{B_1}(\sigma_z)_{B_2}$
$\|\Psi^5\rangle_{B_1B_2}\|00\rangle_{B_3B_4}$	$U(\sigma_z)_{B_1}(\sigma_z)_{B_3}$
$\|\Psi^6\rangle_{B_1B_2}\|00\rangle_{B_3B_4}$	$U(\sigma_z)_{B_2}(\sigma_z)_{B_3}$
$\|\Psi^7\rangle_{B_1B_2}\|00\rangle_{B_3B_4}$	$U(\sigma_x)_{B_2}(\sigma_x)_{B_4}\mathrm{T}B_1B_2,B_3(U_{\mathrm{C-NOT}})_{B_3B_1}(U_{\mathrm{C-NOT}})_{B_3B_2}(U_{\mathrm{C-NOT}})_{B_3B_4}$ $(U_{\mathrm{C-NOT}})_{B_1B_3}(\sigma_z)_{B_1}(\sigma_z)_{B_3}$
$\|\Psi^8\rangle_{B_1B_2}\|00\rangle_{B_3B_4}$	$U(\sigma_x)_{B_2}(\sigma_x)_{B_4}\mathrm{T}B_1B_2,B_3(U_{\mathrm{C-NOT}})_{B_3B_1}(U_{\mathrm{C-NOT}})_{B_3B_2}$ $(U_{\mathrm{C-NOT}})_{B_3B_4}(U_{\mathrm{C-NOT}})_{B_1B_3}(\sigma_z)_{B_2}(\sigma_z)_{B_3}$
$\|\Psi^9\rangle_{B_1B_2}\|00\rangle_{B_3B_4}$	$U(\sigma_x)_{B_3}(\sigma_x)_{B_4}\mathrm{T}B_1B_3,B_2(U_{\mathrm{C-NOT}})_{B_2B_1}(U_{\mathrm{C-NOT}})_{B_2B_3}(U_{\mathrm{C-NOT}})_{B_2B_4}$ $(U_{\mathrm{C-NOT}})_{B_1B_2}$
$\|\Psi^{10}\rangle_{B_1B_2}\|00\rangle_{B_3B_4}$	$U(\sigma_x)B_3(\sigma_x)_{B_4}\mathrm{T}B_1B_3,B_2(U_{\mathrm{C-NOT}})_{B_2B_1}(U_{\mathrm{C-NOT}})_{B_2B_3}(U_{\mathrm{C-NOT}})_{B_2B_4}$ $(U_{\mathrm{C-NOT}})_{B_1B_2}(\sigma_z)_{B_1}(\sigma_z)_{B_2}$
$\|\Psi^{11}\rangle_{B_1B_2}\|00\rangle_{B_3B_4}$	$U(\sigma_x)B_1(\sigma_x)_{B_4}\mathrm{T}B_1B_2,B_3(U_{\mathrm{C-NOT}})_{B_3B_1}(U_{\mathrm{C-NOT}})_{B_3B_2}(U_{\mathrm{C-NOT}})_{B_3B_4}$ $(U_{\mathrm{C-NOT}})B_2B_3$
$\|\Psi^{12}\rangle_{B_1B_2}\|00\rangle_{B_3B_4}$	$U(\sigma_x)B_1(\sigma_x)_{B_4}\mathrm{T}B_1B_2,B_3(U_{\mathrm{C-NOT}})_{B_3B_1}(U_{\mathrm{C-NOT}})_{B_3B_2}(U_{\mathrm{C-NOT}})_{B_3B_4}$ $(U_{\mathrm{C-NOT}})_{B_2B_3}(\sigma_z)_{B_1}(\sigma_z)_{B_2}$
$\|\Psi^{13}\rangle_{B_1B_2}\|00\rangle_{B_3B_4}$	$U(\sigma_x)B_3(\sigma_x)_{B_4}\mathrm{T}B_1B_3,B_2(U_{\mathrm{C-NOT}})_{B_2B_1}(U_{\mathrm{C-NOT}})_{B_2B_3}(U_{\mathrm{C-NOT}})_{B_2B_4}$ $(U_{\mathrm{C-NOT}})_{B_1B_2}(\sigma_z)_{B_1}(\sigma_z)_{B_3}$
$\|\Psi^{14}\rangle_{B_1B_2}\|00\rangle_{B_3B_4}$	$U(\sigma_x)_{B_3}(\sigma_x)_{B_4}\mathrm{T}B_1B_3,B_2(U_{\mathrm{C-NOT}})_{B_2B_1}(U_{\mathrm{C-NOT}})_{B_2B_3}(U_{\mathrm{C-NOT}})_{B_2B_4}$ $(U_{\mathrm{C-NOT}})_{B_1B_2}(\sigma_z)_{B_2}(\sigma_z)_{B_3}$
$\|\Psi^{15}\rangle_{B_1B_2}\|00\rangle_{B_3B_4}$	$U(\sigma_x)_{B_1}(\sigma_x)_{B_4}\mathrm{T}B_1B_2,B_3(U_{\mathrm{C-NOT}})_{B_3B_1}(U_{\mathrm{C-NOT}})_{B_3B_2}(U_{\mathrm{C-NOT}})_{B_3B_4}$ $(U_{\mathrm{C-NOT}})_{B_2B_3}(\sigma_z)_{B_1}(\sigma_z)_{B_3}$
$\|\Psi^{16}\rangle_{B_1B_2}\|00\rangle_{B_3B_4}$	$U(\sigma_x)_{B_1}(\sigma_x)_{B_4}\mathrm{T}B_1B_2,B_3(U_{\mathrm{C-NOT}})_{B_3B_1}(U_{\mathrm{C-NOT}})_{B_3B_2}(U_{\mathrm{C-NOT}})_{B_3B_4}$ $(U_{\mathrm{C-NOT}})_{B_2B_3}(\sigma_z)_{B_2}(\sigma_z)_{B_3}$

2　结论

本文提出了在采用正交完备基测量情况下，利用两个 EPR 对作为量子信道实现四粒子 W 纠缠态隐形传输的方案. 在这个方案中，由于采用了正交完备基作为测量基，使得发送方 Alice 所做的测量计算大量减少. 发送方通过经典信道告知接收方自己的测量结果，接收方通过相应的幺正变换就可使四粒子的 W 态以 100% 的概率实现隐形传输. 整个过程只需要一个正交完备基测量和简单的幺正变换，实现更为容易.

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Teleportation of Four Particles W State Through Two EPR States

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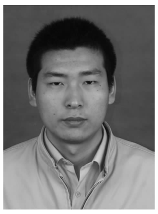
Abstract: In order to reduce the measurement times and computation of quantum teleportation, a scheme for teleportation of four-particle W state via two EPR states is proposed. The sender Alice only do one orthogonal complete basises measurement on her own particles in the unknown Four-particles and two EPR states, by the means of 16 orthogonal complete measure basises. Then the sender inform the 16 kinds of measurement results to the receiver by classical channel, the receiver introduce two auxiliary particle B_3B_4, and do some proper transformation(Toffoli gate, C-Not gate, Pauli-X gate, and Pauli-Z gate) on his own particles. As a result, the 16 kinds of collapse modes will be all restored. In other words, the teleportation of four-particle W state is completely realized. Based on quantum mechanics of superposition operator and the transformation operator, the collapses states can be easily obtained, and Bob's unitary transformation can also be easily given. Because of using orthogonal complete measurement basises method, the sender only need to do a little measurement. This scheme only need one orthogonal complete basises measurement and a simply unitary transmission, which can be realized easily.

Key words: Quantum teleportation; Orthogonal complete measure basises; Four-particle W state



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