The Innsbruck quantum teleportation experimental scheme can be modified to the unconditional one

Wang Xiang-bin*
Imai Quantum Computation and Information project, ERATO, Japan Sci. and Tech. Corp.
Daini Hongo White Bldg. 201, 5-28-3, Hongo, Bunkyo, Tokyo 113-0033, Japan

Abstract

We give a simple way to deterministically rule out the event that two pairs of photons are generated in the same side of the nonlinear crystal in the type II parametric downconversion. By this new scheme, everytime when the concidence is observed it is indeed an event that one pair of photons is generated in each side of the crystal therefore the Innsbruck quantum teleportation experiment (Bouwmeester D et al, Nature 390, 575(1997)) can be modified into the unconditional one.

As it is well known that [1], if two remote parties, Alice and Bob share an entangled state e.g.

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|H\rangle_2|V\rangle_3 - |V\rangle_2|H\rangle_3)$$ (1)

where $H$ and $V$ are for the horizontal polarization and vertical polarization respectively, Alice may teleport an unknown state $|\chi\rangle_1$ to Bob by making a joint measurement to mode 2 and 3 in the Bell basis. Here the subscripts are used to label each photons. The 4 states for the Bell basis are

$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|H\rangle|V\rangle \pm |V\rangle|H\rangle)$$ (2)

*email: wang@qci.jst.go.jp
and

\[ |\Phi^\pm\rangle = \frac{1}{\sqrt{2}} (|H\rangle|H\rangle \pm |V\rangle|V\rangle). \] (3)

To let Bob recover the state \(|\chi\rangle\) on particle 3, Alice broadcasts her measurement results and Bob will then take a local unitary transformation to particle 3 according to Alice’s result. The first experimental test of the quantum teleportation is done by the Innsbruck group [2]. In the experiment, both the entangled state \(|\Psi^-\rangle\) and the teleported state \(|\chi\rangle\) are produced by the type II parametric downconversion. As it was commented in [3], in that set-up there is a comparable probability of generating two pairs in one side of the nonlinear crystal when the pump light is reflected back while generating nothing in the otherside. Taking this factor into consideration, though it has nontrivially verified the fact of quantum teleportation, the Innsbruck experimental set-up cannot be really used as an unconditional quantum teleportation machine to teleport an unknown state, since the average fidelity there does not exceed the threshold of 3/4 without a destroying post selection. It was then argued [4] that the issue can be in principle solved given a very good photon detector which distinguishes one photon and two photons. However, such a very good photon detector is not possibly available by our current technology. To overcome this technical difficulty, one may immediately consider using the cascaded detection [5]. As it was investigated in ref [5], to keep the normal experimental efficiency, the cascaded detection requires the photon detector to detect one photon successfully in a rate higher than 98%. This is obviously not possible with the current technology. Here we show that actually the problem can be solved in a very simple and very feasible way.

Let us first consider the well-known properties of a polarizing beam splitter (PBS). As it is shown in Fig.1, a PBS reflects a horizontally polarized photon and transmits a vertically polarized photon. We can use this property to filter one term in the two pair state. We use a scheme as shown in Fig. 2. We require the following concidence for a successful quantum teleportation:

1. Both the detectors of D₁ and D₂ must be fired.
2. One and only one in \(D_3\) and \(D_4\) is fired.

Let's first consider the consequence of the second item in the concidence. Suppose after it is pumped, the crystal actually generates two pairs in the left side and nothing in the right side. As it was shown in ref. [6], the state for the two pair term can be explicitly written in the following form

\[
|\psi\rangle_{14} = \frac{1}{\sqrt{3}}(2H_1|2V\rangle_4 - |HV\rangle_1|HV\rangle_4 + |2V\rangle_1|2H\rangle_4).
\] (4)

In such a case, beam 4 must include two photons. The middle term in the right side of eq.(4), i.e., the term with one horizontal and one vertical photon in beam 4 is immediately ruled out by the second item in our definition of coincidence. Because if this term works, there must be one photon in each side of the PBS therefore both \(D_3\) and \(D_4\) will be fired, instead of only one of them being fired. Furthermore, let's consider the event that one detector in \(D_3\) and \(D_4\) is fired. For simplicity, we assume that \(D_3\) is fired and \(D_4\) is silent. We still suppose that actually there are two pairs generated in the left side of the crystal and nothing in the right side. In such a case, since we have already observed that only \(D_3\) is fired, beam 4 must include 2 horizontal photons only. According to eq.(4), beam 1 must include 2 vertical photons only. Now let's see what happens after beam 1 reaches the beam splitter. A beam splitter will never change the polarization of these two photons. Since we have placed a horizontal polarizer before detector \(D_1\) and a vertical polarizer before \(D_2\), therefore in the case that beam 1 includes two vertical photons, the detector \(D_1\) will be never fired. Consequently, the event is abandoned by the item 1 of our definition of the coincidence. Similarly, if \(D_4\) is fired and \(D_3\) silent, the detector \(D_2\) will never be fired. Again, the event is abandoned by the item 1 of our definition of the coincidence. So far we have seen that our scheme can indeed rule out all three terms in the right side of eq.(4). That is to say, we can safely filter all the bad events that two pairs are generated in the left side of the crystal and nothing generated in the right side. However, a good event will still have a chance of 50% probability to survive. The good event is that one pair of photons in each side of the crystal is generated and beam 1 and beam 2 are collapsed to the state \(|\Psi^-\rangle\) after
they reach the beam splitter. In such a case, we have half a probability that both \(D_1\) and \(D_2\) are fired. As it has already shown that, in all the other collapsing for beam 1 and beam 2, at most one detector in \(D_1\) and \(D_2\) is fired. Therefore all other collapsing events are ruled out and we draw the conclusion that, whenever we observed a concidence, the state in beam 1 has been teleported to beam 3 successfully.

In summary, we have given a simple way to make an unconditional quantum teleportation. Our scheme is just a slight modification of the Innsbruck [2,7] scheme which has been experimentally tested already. We believe our scheme can be carried out easily based on the current technology. Our scheme can be used to teleport an arbitrary linear superposition state of \(|H\rangle\) and \(|V\rangle\) by just take an appropriate rotation operation on beam 1 and beam 4.

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FIG. 1. A schematic diagram for the properties of a polarizing beam splitter (PBS). It reflects a vertically polarized photon (V) and transmits a horizontally polarized photon (H).
FIG. 2. A schematic diagram for an unconditional quantum teleportation set-up. NC represents for the nonlinear crystal used in the type II parametric downconversion. BS indicates a beam splitter. PBS is a polarizing beam splitter. $D_i$ is the $i$'th photon detector. $P_H$ and $P_V$ are horizontal polarizer and vertical polarizer respectively. Whenever we find the concidence that both $D_1$ and $D_2$ are fired and one and only one detector in $D_3$ and $D_4$ is fired, the state in beam 1 is teleported to beam 3. This set-up can be used to teleport an arbitrary unknown state in the linear superposition of $|H\rangle$ and $|V\rangle$. $D_3$ and $D_4$ plays a role to both partially rule out the satte defined in eq.(4) and prepare the state for beam 1.