Teleportation of a Vacuum–One-Photon Qubit

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We report the experimental realization of teleporting a one-particle entangled qubit. The qubit is physically implemented by a two-dimensional subspace of states of a mode of the electromagnetic field, specifically, the space spanned by the vacuum and the one-photon state. Our experiment follows the line suggested by Lee and Kim [Phys. Rev. A 63, 012305 (2000)] and Knill, Laflamme, and Milburn [Nature (London) 409, 46 (2001)]. An unprecedented large value of the teleportation “fidelity” has been attained: $F = (95.3 \pm 0.6)\%$.

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In their pioneering paper Bennett, Brassard, Crepeau, Jozsa, Peres, and Wootters introduced the concept of teleportation of a quantum state [1]. Since then, teleportation came to be recognized as one of the basic methods of quantum communication and, more generally, as one of the basic ideas of the whole field of quantum information. Following the original teleportation paper and its continuous-variables version [2], an intensive experimental effort started for the practical realization of teleportation. The quantum state teleportation (QST) has been realized in a number of experiments [3–6]. In a beautiful example of ingenuity, although starting from a common theme, each of these experiments followed a completely different route and principle. In the present paper, we report a new teleportation experiment following yet another different idea. In our experiment, we consider a qubit which is physically realized not by a particle but by a mode of the electromagnetic (e.m.) field, and whose orthogonal base states $|0\rangle$, $|1\rangle$ are the vacuum state and the one-photon state, respectively. We designed our scheme by adapting a method proposed by Knill, Laflamme, and Milburn [7] to make it experimentally easily feasible. We later learned that our method is identical to that proposed by Lee and Kim [8] and also closely related to [9]. In our experiment, the role of the two particles in a singlet state by Lee and Kim [8] and also closely related to [9]. In our experiment, the role of the two particles in a singlet state by Lee and Kim [8] and also closely related to [9]. In our experiment, the role of the two particles in a singlet state by Lee and Kim [8] and also closely related to [9]. In our experiment, the role of the two particles in a singlet state by Lee and Kim [8] and also closely related to [9]. In our experiment, the role of the two particles in a singlet state by Lee and Kim [8] and also closely related to [9]. In our experiment, the role of the two particles in a singlet state by Lee and Kim [8] and also closely related to [9].

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qubit to be teleported. Suppose now that the qubit $k_s$ is in an arbitrary pure state,
\[ \alpha |0\rangle_S + \beta |1\rangle_S . \]  

The overall state of the system and the nonlocal channel is then
\[ |\Phi_{\text{total}}\rangle = 2^{-1/2}(\alpha |0\rangle_S + \beta |1\rangle_S)(|1\rangle_A|0\rangle_B - |0\rangle_A|1\rangle_B) \]
\[ = 2^{-1/2}\alpha |\Psi^1\rangle_{SA}|1\rangle_B + 2^{-1/2}\beta |\Psi^2\rangle_{SA}|0\rangle_B \]
\[ + \frac{1}{2} |\Psi^3\rangle_{SA}(\alpha |0\rangle_B + \beta |1\rangle_B) \]
\[ + \frac{1}{2} |\Psi^4\rangle_{SA}(\alpha |0\rangle_B - \beta |1\rangle_B) , \]  

where the states $|\Psi^i\rangle_{SA}$, $i = 1, 2, 3, 4$ are defined below in Eq. (3). The teleportation proceeds with Alice performing a partial Bell measurement. She combines the modes $k_s$ and $k_A$ on a symmetric (i.e., 50:50) beam splitter $BS_A$ whose output modes $k_1$ and $k_2$ are coupled to two detectors $D_1$ and $D_2$, respectively (see Fig. 1). The action of $BS_A$ on the field operators is expressed by
\[ \hat{\alpha}^\dagger_A = 2^{-1/2}(\hat{a}^\dagger - \hat{a}) \hat{a}, \]
\[ \hat{a}^\dagger = 2^{-1/2}(\hat{a}^\dagger + \hat{a}) \hat{a} \], where labels 1, 2 refer to modes $k_1, k_2$. As a consequence, we obtain
\[ |\Psi^1\rangle_{SA} = |0\rangle_S|0\rangle_A = |0\rangle_1|0\rangle_2 , \]
\[ |\Psi^2\rangle_{SA} = |1\rangle_S|1\rangle_A = 2^{-1/2}(|0\rangle_1|1\rangle_2 - |1\rangle_1|0\rangle_2) , \]
\[ |\Psi^3\rangle_{SA} = 2^{-1/2}(|0\rangle_S|1\rangle_A - |1\rangle_S|0\rangle_A) = |1\rangle_1|1\rangle_2 , \]
\[ |\Psi^4\rangle_{SA} = 2^{-1/2}(|0\rangle_S|1\rangle_A + |1\rangle_S|0\rangle_A) = |0\rangle_1|1\rangle_2 , \]  

The state $|\Psi^3\rangle_{SA}$ is a Bell-type state [1]. From Eq. (3) we see that its realization implies a single photon arriving at the detector $D_1$ and no photons at $D_2$. Similarly, $|\Psi^4\rangle_{SA}$ is a Bell-type state and it implies a single photon arriving at the detector $D_2$ and no photons at $D_1$. In both of these cases the teleportation is successful. Indeed, when Alice finds $|\Psi^3\rangle_{SA}$, Bob’s e.m. field ends up in the state $|\Phi\rangle = (\alpha |0\rangle_B + \beta |1\rangle_B)$ which is identical to the state to be teleported, while when Alice finds $|\Psi^4\rangle_{SA}$, Bob ends up with the state $|\Phi\rangle = (\alpha |0\rangle_B - \beta |1\rangle_B) = \sigma_\gamma |\Phi\rangle$ which is identical to the state to be teleported up to a phase shift $\Delta = \pm \pi$. The states $|\Phi\rangle$ and $|\Phi\rangle$ are connected by a unitary transformation expressed by the Pauli spin operator $\sigma_\gamma$. Bob can easily correct the phase shift $\Delta$ upon finding out Alice’s result. In practice, this phase correction procedure, generally referred to as “active teleportation” [3] is carried out automatically by means of a fast electro-optic Pockels cell (EOP) inserted in mode $k_B$ and triggered by $D_2$. On the other hand, when Alice finds $|\Psi^1\rangle_{SA}$ or $|\Psi^2\rangle_{SA}$ the teleportation fails. From Eq. (3) we see that teleportation is successful in 50% of the cases.

A major technical difficulty in the above teleportation scheme is the preparation and manipulation of the pure states to be teleported. Indeed, they are superpositions of the vacuum and one-photon states of the mode $k_s$. Manipulating such states and, in particular having control about the relative phase between the vacuum and one-photon states is quite problematic. This can be realized in principle, for example, by homodyning techniques as described in [15]. Here, however, we avoid the problem altogether, by teleporting appropriate entangled states instead of pure ones. The states we consider are of the form
\[ |\Psi\rangle_{SA} = (\alpha |0\rangle_S|1\rangle_A + \beta |1\rangle_S|0\rangle_A) , \]
where $\sigma_a$ is an “ancilla” mode. These states are in fact simple single-photon states and can be easily obtained by, for example, letting a single photon impinge on a beam splitter ($BS_S$ in Fig. 1) with reflectivity $r_S$ and transmissivity $t_S$, $k_s$ being the reflected mode and $k_S$ the transmitted one. For the sake of simplicity and without loss of generality, we assume that $\alpha$ and $\beta$ are real numbers.

In summary, in our experiment we have four qubits: $k_A$ and $k_B$ which constitute the nonlocal communication channel, $k_S$ which represents the system, i.e., the qubit to be teleported, and $k_a$ the ancilla. The special states of these four qubits which are used in the experiment are physically implemented by exactly two photons. The state of the qubit $k_S$ is teleported to Bob into the state of the qubit $k_B$, thus the overall state $|\Psi\rangle_{SA}$ will now be transferred into the state of the qubits $k_B$ and $k_a$. To verify that the state has been teleported, we transmit the qubit $k_a$ to Bob. The QST verification consists simply by mixing the modes $k_B$ and $k_a$ at a beam splitter ($BS_B$) similar to the one which was used to produce the state to be teleported $|\Psi\rangle_{SB}$. We shall see that the optimum QST verification, viz. implying the maximum visibility $V$ of the corresponding interferometric patterns, is obtained by adopting equal optical parameters for both $BS_S$ and $BS_B$, i.e., $|r_S| = |r_B| = |r_B| = \beta$. This verification procedure is generally referred to as “passive teleportation” [3]. Finally, note that the “ancillary” single photon emitted on mode $k_a$ indeed provides the “clock” pulse that is needed to retrieve at Bob’s side the full information content of the vacuum state $|0\rangle_B$ entangled within the nonlocal teleportation channel, i.e., with the singlet state $|\Phi\rangle_{\text{singlet}}$ [14].

The experimental setup is shown in Fig. 1. A nonlinear LiIO$_3$ crystal slab, 1.5 mm thick with parallel antireflection coated faces, cut for Type I phase matching is pumped by a single mode UV cw argon laser with wavelength (wl) $\lambda_p = 363.8$ nm and with an average power $\approx 100$ mW. The UV laser beam was focused close to the crystal by
shown, including the high-voltage Pockels cell (EOP) in Fig. 1, the complete scheme for frequency of the beams within a 20 nm bandwidth. In before detection two equal interference tors were Si-avalanche EG&G-SPCM200 counting mod-
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collecting efficiency by the Alice’s detector system of the spontaneous parametric down-conversion (SPDC) fluores-
cence [16]. The two SPDC emitted photons have equal w1 λ = 727.6 nm and are spatially selected by two pin-
holes with equal apertures with diameter 0.5 mm placed at a distance of 50 cm from the crystal. One of the pho-
tons generates on the two output modes kA and kB of a 50:50 beam splitter (BS) the singlet state |Δ⟩ singlet providing
the nonlocal teleportation channel. The other photon generates the state |ψ⟩Sa, i.e., the quantum superposition of
the state to be teleported and the one of the ancilla at the output of a variable beam splitter BSa consisting of the
combination of a λ/2 polarization rotator and of a calcite crystal. Furthermore, micrometric changes of the mutual
phase φ of the kS and kA modes interfering on BSa were obtained by a piezoelectrically driven mirror M. All detec-
tors were Si-avalanche EG&G-SPCM200 counting modules having nearly equal quantum efficiencies QE = 0.45.
Before detection two equal interference filters selected the frequency of the beams within a 20 nm bandwidth.
In Fig. 1, the complete scheme for “active” teleportation is shown, including the high-voltage Pockels cell (EOP) in-
serted on the mode kB. In the same figure is reported the interferometric scheme for “passive teleportation” which is also
adopted for the verification of the correct implementa-
tion of the active protocol, as we shall see.

We have realized experimentally the passive teleporta-
tion protocol. By this we mean that Bob does not modify
his state according to the results obtained by Alice.
Instead Bob passes his state unmodified to the verification
stage. The verification stage consists of combining the
mode kB (which now contains the teleported state) with the
ancilla mode ka at a beam splitter BSb, as said. In order to
check the overall mode alignment, we first checked at Alice’s site the two-photon Ou-Mandel interference across
the beam splitter BSa between the modes kS and kA that are coupled to detectors D1 and D2, respectively. We
obtained a two-photon interference pattern with a visibility V a = 96. In a similar way, we checked at Bob’s site the
Ou-Mandel interference across BSb between the modes kB and ka coupled to the respective detectors D1, D2, ob-
taining V b = 92. The QST verification experiment has been carried out first with a 50:50 beam splitter BSj, i.e.,
with optical parameters |rj| = |sj| = 2−1/2. The maximum visibility of the verification fringe pattern is obtained by selecting the same values of the parameters for the test
beam splitter BSj, as said. Then we measured the coinci-
dence counts between D1, D2 and D1, D∗ 2 . By a straight-
forward calculation, we expect

\[ D_1 - D_1^* = D_2 - D_2^* = \frac{1}{2} \sin^2 \frac{\phi}{2}, \]
\[ D_1 - D_2^* = D_2 - D_1^* = \frac{1}{2} \cos^2 \frac{\phi}{2}, \]

where (D1 − D1) expresses the probability of a coinci-
dence detected by the pair D1, D1 in correspondence with
the realization of either one of the states: |ψ⟩Sa, |ψ⟩Sa.
The experimental plots shown in Fig. 2, obtained by vary-
ing the position X = (2−3/2)λ φ/π of the mirror M, are
in agreement with the theory [Eq. (5)]. This agreement is
further substantiated by the data reported in Fig. 3 corre-
sponding to a similar verification experiment carried out
with different optical parameters for BSj: |rj| = 0.20, |sj| = 0.80. There it is shown that the maximum visi-
ibility V is attained for values of \( \alpha^2 = 1 - \beta^2 \) that are
equal to |rj|2 or to |sj|2 depending on which pair of de-
tectors are excited. In the same figure is also reported a
single value V = 0.91 related to the fully symmetric case:

|rB|2 = |sB|2 = \( \alpha^2 = \beta^2 = \frac{1}{2} \). 

Note that by assuming perfect detectors, i.e., with
QE = 1, the above QST verification procedure involving
the ancilla mode ka enables a fully noise-free teleportation
procedure. Indeed, if no photons are detected at Alice’s
site, i.e., by D1 and/or D2, while photons are detected
at Bob’s site by D1 and/or D2, we can safely conclude
that the “idle” Bell state |ψ⟩Sa has been created. If on
the contrary no photons are detected at Bob’s site while
photons are detected at Alice’s site, we must conclude
that the other idle Bell state |ψ⟩Sa has been realized.
The data collected in correspondence with these idle events can
automatically be discarded by the electronic coincidence
circuit. In addition to that, note that the effect of the above
verification procedure involving the ancilla mode ka keeps
holding within the active teleportation scheme. Indeed, if
the D2-driven electro-optic (EOP) phase modulator works
correctly within the active scheme, the detector D∗ 2 should
be found to be always inactive. Note that by the present
method an unprecedented large value of the QST “fidelity”
has been attained: F = ⟨φin|ρout|φin⟩ = (1 + V)/2 =
(95.3 ± 0.6)%.
Our present effort is directed towards the completion of the teleportation picture by the realization of the active scheme. The main technical problem resides in the relatively large time needed to activate a high-voltage EOP device by a single-photon detection. The best result we have attained thus far for the 1 kV switching time across an EOP modulator is about 10 ns. This figure would enable us to achieve the goal in the near future by the adoption of small $\lambda/2$-voltage EOP devices possibly in conjunction with the use of optical fibers.

In conclusion, we have given the experimental all optical demonstration of a key quantum information protocol in a new conceptual framework. This one is based on the nonlocal properties of a single photon and on the adoption of the Fock states of any single optical mode as basis states of the relevant Hilbert space. We have also shown that these states can be entangled. This new approach, which necessarily involves the adoption of synchronizing clock states, is expected to be far reaching as it can be generalized to all protocols of quantum information and quantum computation. A theoretical analysis of the new perspectives is reported elsewhere.

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