Quantum Teleportation with Photons

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Motivation

- The distribution of single qubits over large distance via quantum teleportation is a key ingredient for realization of a quantum network

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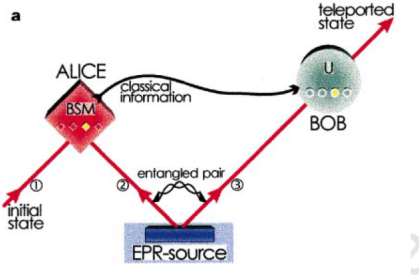
- The distribution of single qubits over large distance via quantum teleportation is a key ingredient for realization of a quantum network
- Quantum teleportation is a secure way to send information

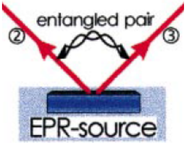
Overview

The quantum teleportation protocol



1. Alice prepares or receives a quantum bit
$\Rightarrow |\psi\rangle_1 = \alpha\,|0\rangle_1 + \beta\,|1\rangle_1\,,$ where: $|\alpha|^2 + |\beta|^2 = 1$

The quantum teleportation protocol



2. A pair of entangled qubits is created and sent to Alice and Bob
   $\Rightarrow |\Psi^-\rangle_{23} = \frac{1}{\sqrt{2}} \left(|01\rangle_{23} - |10\rangle_{23} \right)$

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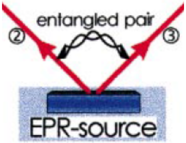

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   $\Rightarrow |\Psi^{-}\rangle_{23} = \frac{1}{\sqrt{2}} \left(|01\rangle_{23} - |10\rangle_{23} \right)$
3. Rewrite the state of the three qubits:

$$
\begin{aligned}
|\psi\rangle_{123} &= \left(\alpha |0\rangle_{1} + \beta |1\rangle_{1} \right) \otimes \frac{1}{\sqrt{2}} \left(|01\rangle_{23} - |10\rangle_{23} \right) \\
&= \frac{1}{4} \sum_{k} \left(|\Psi_{k}\rangle_{12} \otimes U_{k} |\psi\rangle_{3} \right),
\end{aligned}
$$

where $|\psi\rangle_{3} = \alpha |0\rangle_{3} + \beta |1\rangle_{3}$, U_{k} is a unitary Matrix, and the $|\Psi_{k}\rangle_{12}$ are Bell states

The quantum teleportation protocol

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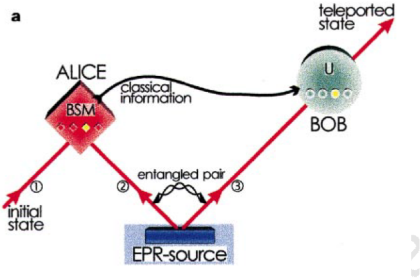
6. Four possible outcomes:

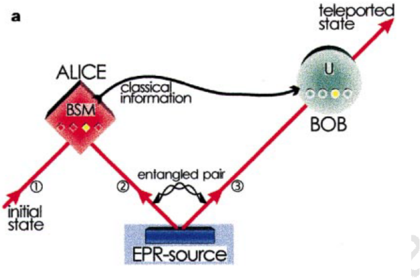
Measurement	**Resulting state**	**Bob's Operation**
$\|\Psi^-\rangle_{12}$	$\|\Psi^-\rangle_{12} \otimes (\alpha \|0\rangle_3 + \beta \|1\rangle_3)$	σ_0
$\|\Phi^-\rangle_{12}$	$\|\Phi^-\rangle_{12} \otimes (\beta \|0\rangle_3 + \alpha \|1\rangle_3)$	σ_1
$\|\Phi^+\rangle_{12}$	$\|\Phi^+\rangle_{12} \otimes (\beta \|0\rangle_3 - \alpha \|1\rangle_3)$	σ_2
$\|\Psi^+\rangle_{12}$	$\|\Psi^+\rangle_{12} \otimes (\alpha \|0\rangle_3 - \beta \|1\rangle_3)$	σ_3

The quantum teleportation protocol



7. Bob performs the appropriate unitary operation on his qubit

The quantum teleportation protocol

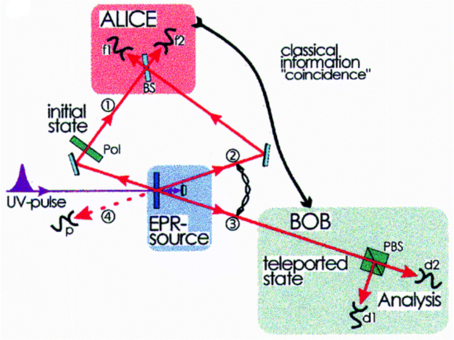


7. Bob performs the appropriate unitary operation on his qubit
8. Bob is now in possession of the qubit Alice wanted to send!!

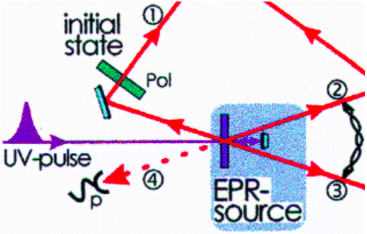
Note: Alice's qubit is destroyed in the measuring process!

Crucial steps:

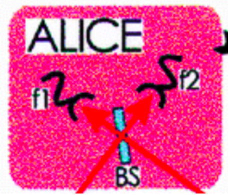
1. Creation of entanglement
2. Realization of Bell-Measurement
3. Analysis of teleported state



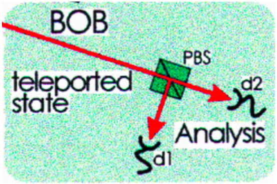
1. Creation of entanglement
   - Entangled photon pair $|\Psi^-\rangle_{23}$ created via type II-Parametric Down Conversion
   - Laser pulse is reflected at mirror and creates $|\Psi^-\rangle_{14}$



2. Realization of Bell-Measurement
    - Photon 1 and 2 superimposed at BS with detectors f1 and f2
    - Coincidence click projects photons 1 and 2 into $|\Psi^-\rangle_{12}$
    - Difference in arrival time $\leq 520\,\mathrm{fs} \equiv$ arrive „simultaneously“



3. Analysis of teleported state
    - Bob knows via CCC if photon 3 is in desired state
    - Polarization is analysed with PBS with detectors d1 and d2



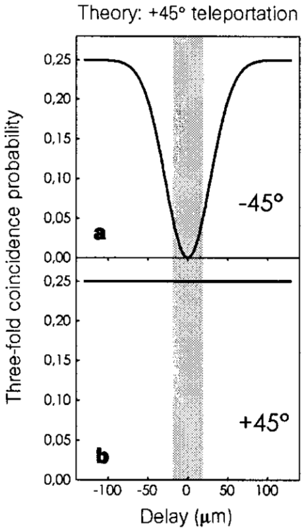
Experiment

Theoretical prediction

Preparation in $+45^{\circ}$-polarization

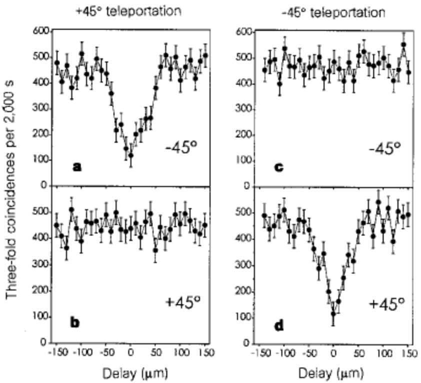
TP-region	Coincidence	d1	d2
Outside	50%	50%	50%
Inside	25%	0%	100%

- Successful teleportation:
  3-fold coincidence d2-f1-f2 with absence of 3-fold coincidence d1-f1-f2



Results

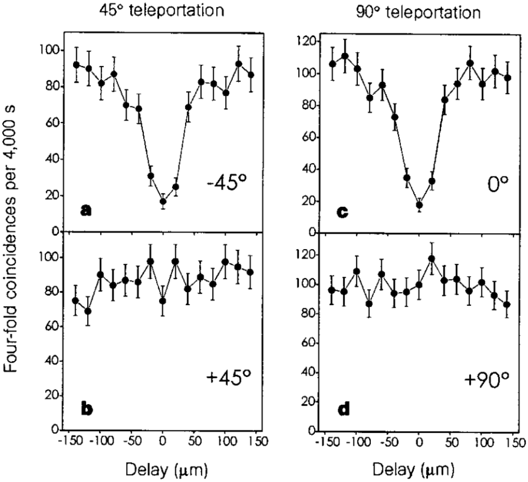
Measured three-fold coincidences



Polarization	Visibility
$+45^\circ$	0.63 ± 0.02
-45°	0.64 ± 0.02
0°	0.66 ± 0.02
90°	0.61 ± 0.02
Circular	0.57 ± 0.02

Results

Measured four-fold coincidences

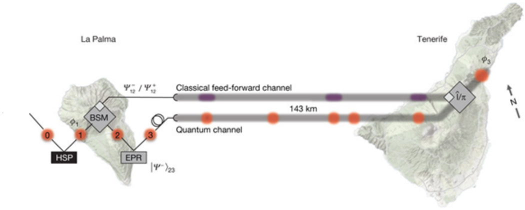


- Visibilities of the dip in the orthogonal polarization are $(70 \pm 3)\,\%$

Summary

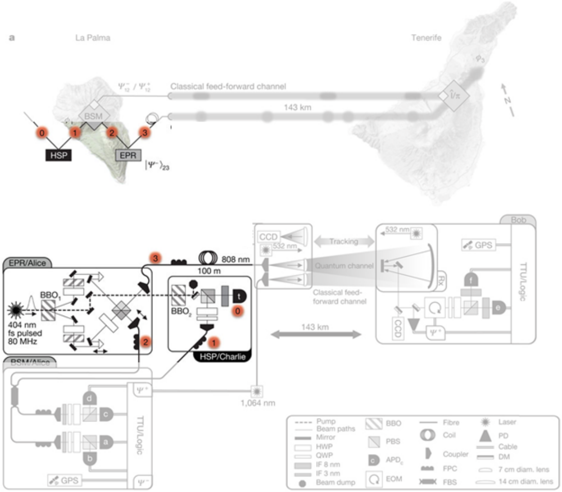
- Teleportation of a single photon achieved at fidelity of 70 %
- Next steps:
  - Show teleportation in other systems
  - Conduct experiments on the fundamental nature of quantum mechanics
  - Provide links between quantum computers
  - Increase teleportation distance

Setup

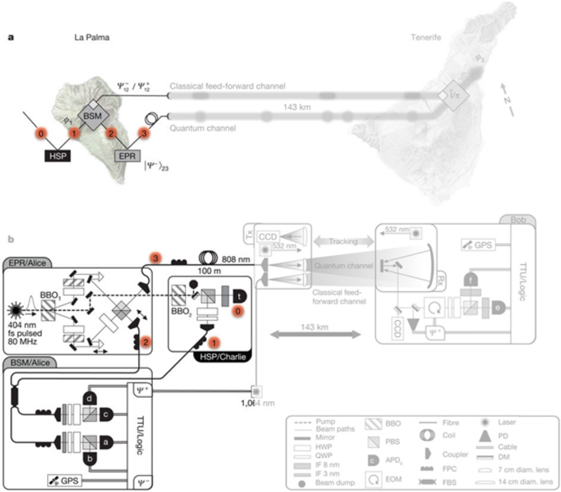


- Physical setup on La Palma (Alice) and Tenerife (Bob)

Setup

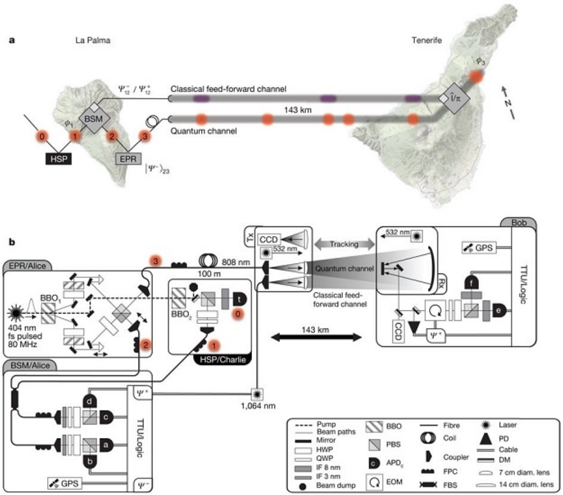


- Creation of photons.
- Photon 1 heralded by click at (t)



- Alice's Bell state measurement.
- $|\Psi^-\rangle_{12} \rightarrow$ clicks at **t-a-d** or **t-b-c**, $|\Psi^+\rangle_{12} \rightarrow$ clicks at **t-a-b** or **t-c-d**

Setup



- Bob's measurement setup
- Classical and quantum channels are separated via dichoric mirror

Feed-Forward

Alice's BSM distinguishes 2 Bell states ($|\Psi^+\rangle$ and $|\Psi^-\rangle$)

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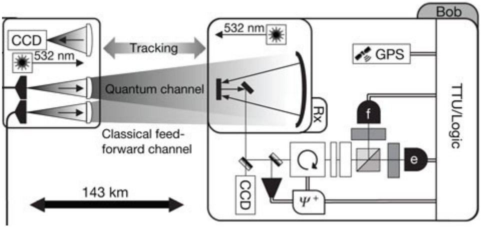

Noise Reduction

Problem: Fluctuations in atmosphere (rain, snow, temperature, etc.) $\Rightarrow$ very low signal-to-noise ratio

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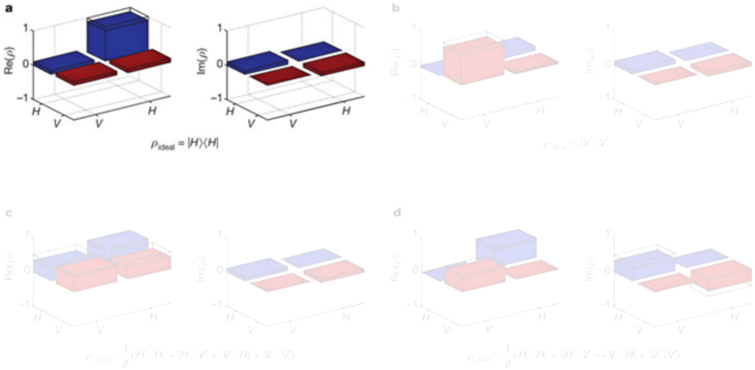
Solutions:

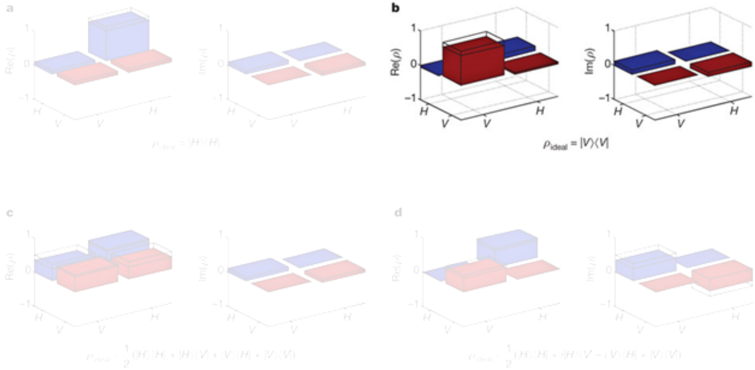
- High creation rates of entangled photon pairs
- Ultra-low dark count detectors with large active area
- Small coincidence windows
- Closed-loop tracking system

- To test the teleportation, a known state is polarization is created (photon 1) and measured by Bob.
- Results shown using density matrix representations.

Input state: $|\psi\rangle = |H\rangle$



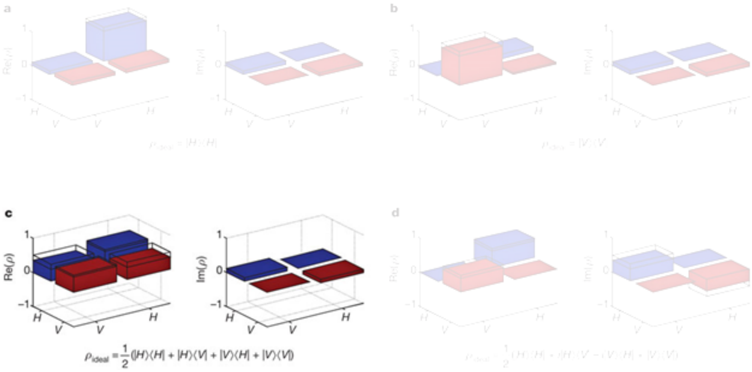
Input state: $|\psi\rangle = |V\rangle$



Results

Density Matrix Representation

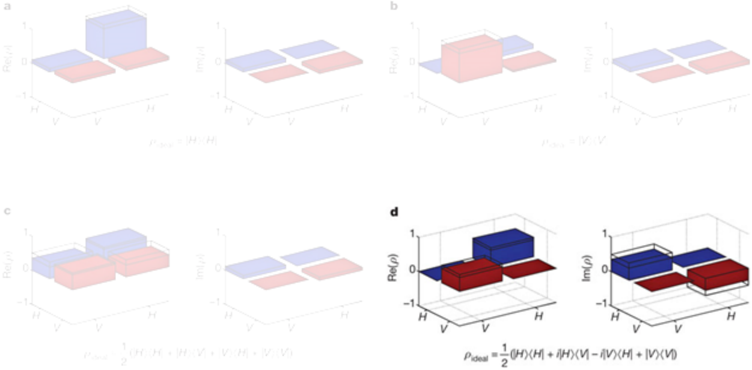
Input state: $|\psi\rangle = |P\rangle = \frac{|H\rangle + |V\rangle}{\sqrt{2}}$



Results

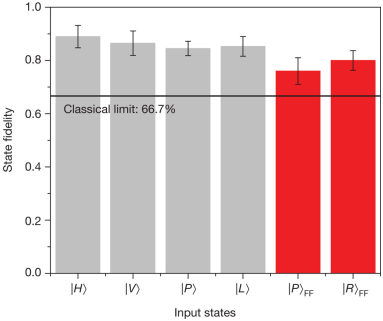
Density Matrix Representation

Input state: $|\psi\rangle = |L\rangle = \frac{|H\rangle - i|V\rangle}{\sqrt{2}}$



Results
Fidelities

Fidelities ($\langle\psi_{ideal}|\,\rho_{meas}\,|\psi_{ideal}\rangle$) are always above classical limit [3]!
(feed-forward results shown in red)



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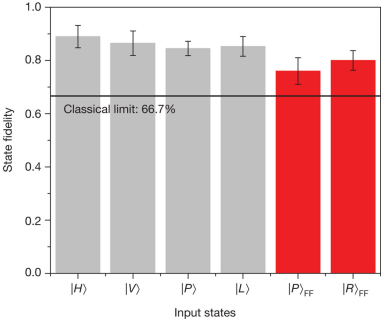

Note: results for $|H\rangle$ *and* $|V\rangle$ with or without feed-forward differ only by global phase

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- We have seen how it can be used to teleport information over 143 km
- First steps to world wide quantum key distribution $\rightarrow$ quantum network

References

1. Dik Bouwmeester, Jian-Wei Pan, Klaus Mattle, Manfred Eibl, Harald Weinfurter & Anton Zeilinger, *Experimental quantum teleportation,* Nature **390**, 575 (1997).
2. Ma, Xiao-Song, et al., *Quantum teleportation over 143 kilometres using active feed-forward,* Nature **489**, 7415 (2012).
3. Serge Massar & Sandu Popescu, *Optimal extraction of information from finite quantum ensembles,* Phys. Rev. Lett. **74**, 1259(1995).