Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Quantum Teleportation with Photons

Jessica Britschgi

Pascal Basler

Bouwmeester, D; Pan, J-W; Mattle, K; et al. "Experimental quantum teleportation". Nature **390**, 575 (1997).

Outline

- The Concept of Quantum Teleportation
- Experimental Realization
- Results

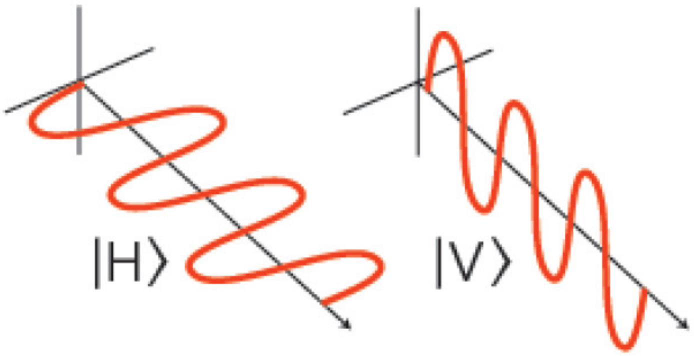
Photon as Qubits

General single photon state: Superposition of horizontal ↔ and vertical ↕ polarization

$$|\psi\rangle = \alpha\,|\leftrightarrow\rangle + \beta\,|\updownarrow\rangle$$

with $|\alpha|^2 + |\beta|^2 = 1$

2-state-system → qubit

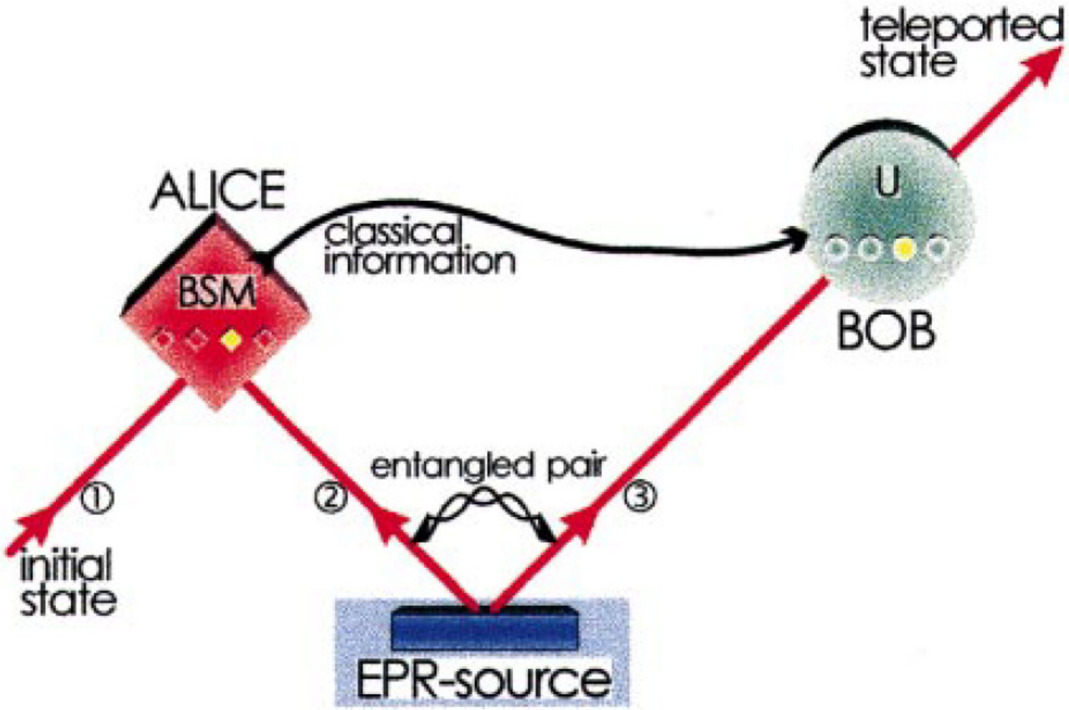


Schematical Setup

Alice wants to transmit an arbitrary state

$$|\psi\rangle_1 = \alpha\,|\leftrightarrow\rangle_1 + \beta\,|\updownarrow\rangle_1$$

to Bob.



They share an entangled Bell state

$$|\psi^-\rangle_{23} = \frac{1}{\sqrt{2}}\left(|\leftrightarrow\rangle_2\,|\updownarrow\rangle_3 - |\updownarrow\rangle_2\,|\leftrightarrow\rangle_3\right)$$

Alice has qubits 1 & 2 , Bob qubit 3.

Global State

Bell states form a complete 2-qubit basis. Rewrite Alice's qubits in Bell basis:

$$
\begin{aligned}
|\chi\rangle_{123} &= |\psi\rangle_1 |\psi^-\rangle_{23} \\
&= (\alpha|\leftrightarrow\rangle_1 + \beta|\updownarrow\rangle_1)\frac{1}{\sqrt{2}}(|\leftrightarrow\rangle_2|\updownarrow\rangle_3 - |\updownarrow\rangle_2|\leftrightarrow\rangle_3) \\
&= \frac{1}{2}\big[|\psi^-\rangle_{12}\boxed{(-\alpha|\leftrightarrow\rangle_3 - \beta|\updownarrow\rangle_3)} = -|\psi\rangle_3 \\
&\quad + |\psi^+\rangle_{12}(-\alpha|\leftrightarrow\rangle_3 + \beta|\updownarrow\rangle_3) \\
&\quad + |\phi^-\rangle_{12}(\beta|\leftrightarrow\rangle_3 + \alpha|\updownarrow\rangle_3) \\
&\quad + |\phi^+\rangle_{12}(-\beta|\leftrightarrow\rangle_3 + \alpha|\updownarrow\rangle_3)\big]
\end{aligned}
$$

Bell-Measurement

Alice performs a projective measurement in Bell basis on her qubits 1 & 2. With a probability of 25% she projects her qubits onto the state

$$\left|\psi^-\right\rangle_{12} = \frac{1}{\sqrt{2}}\left(\left|\leftrightarrow\right\rangle_1 \left|\updownarrow\right\rangle_2 - \left|\updownarrow\right\rangle_1 \left|\leftrightarrow\right\rangle_2\right)$$

Then Bob has the qubit

$$-\left|\psi\right\rangle_3 = -\alpha\left|\leftrightarrow\right\rangle_3 - \beta\left|\updownarrow\right\rangle_3$$

No Violation of Fundamental Principles!

With a probability of 75% Alice projects her qubits onto a different Bell state. Bob will then not get the correct state, but can transform his state into the correct state by applying a unitary, depending on Alice‘s outcome.

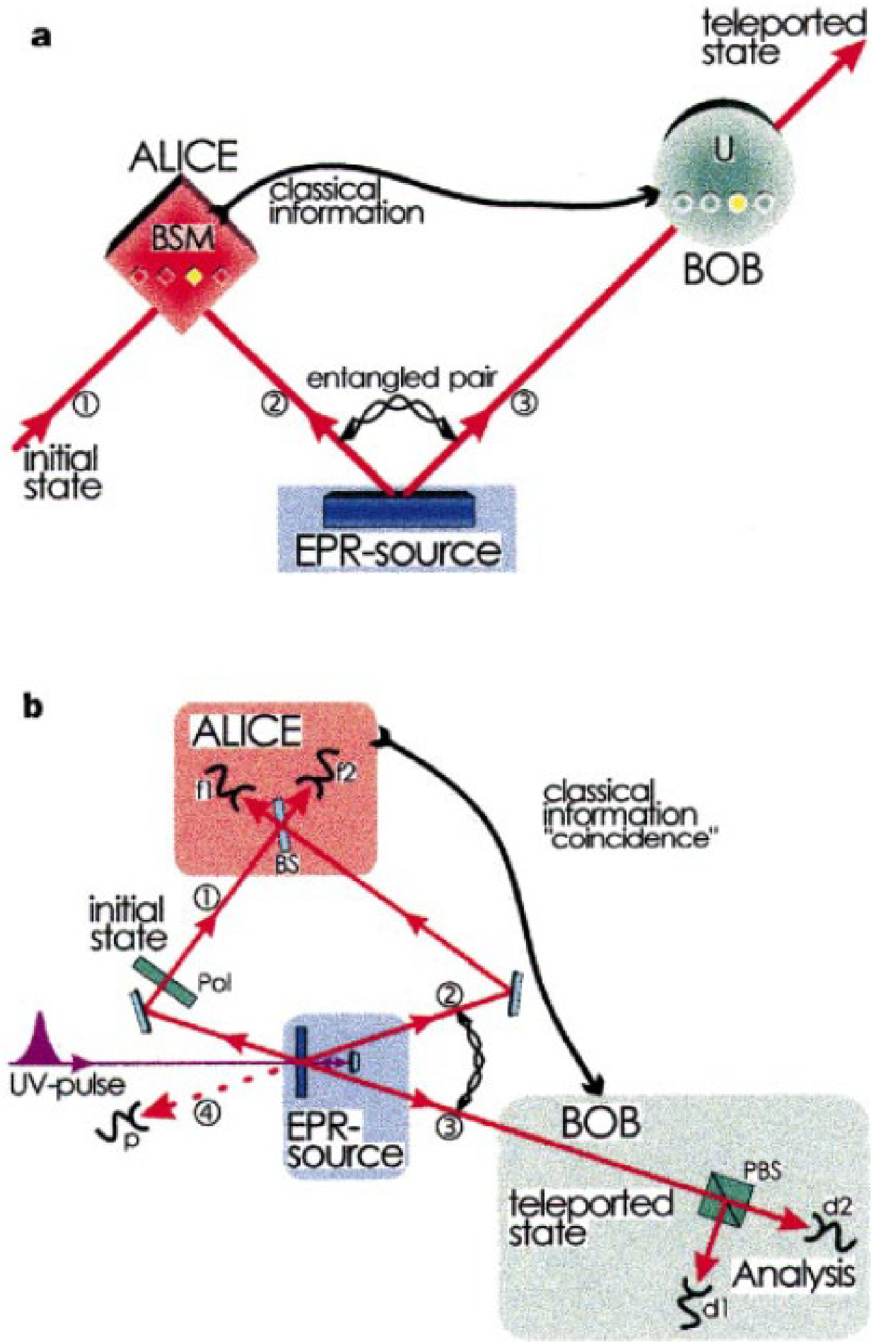
Alice has to tell Bob her measurement result over a classical channel → NO superluminal communication is possible!

After Alice‘s measurement she cannot recover the teleported state → NO violation of No-Cloning-Theorem!

Experimental Setup

- No experimentally realized procedure to distinguish all four Bell states, but: Antisymmetric Bell state $|\psi^-\rangle_{12}$ can be distinguished from other three (symmetric).
- Bob performs no post-processing, drops state if Alice does not project onto $|\psi^-\rangle_{12}$

→ Teleportation works only in 25% of all cases!



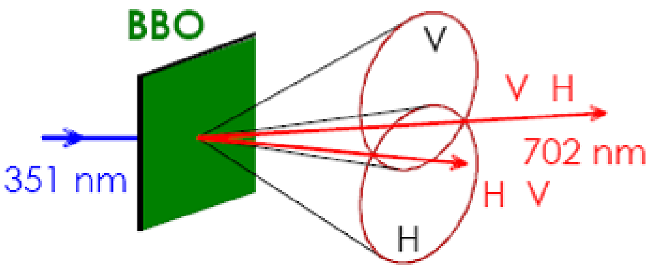
Entanglement Production

parametric down-conversion

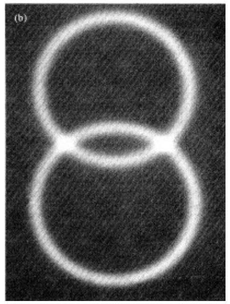
- 1 UV-photon ➔ 2 "red" photons
- conservation of

  energy $\omega_p = \omega_s + \omega_i$

  momentum $\vec{k}_p = \vec{k}_s + \vec{k}_i$
- Polarisationskorrelationen (typ II)



$$|\Psi^-\rangle = \tfrac{1}{\sqrt{2}}\left(|H\rangle|V\rangle - |V\rangle|H\rangle\right)$$



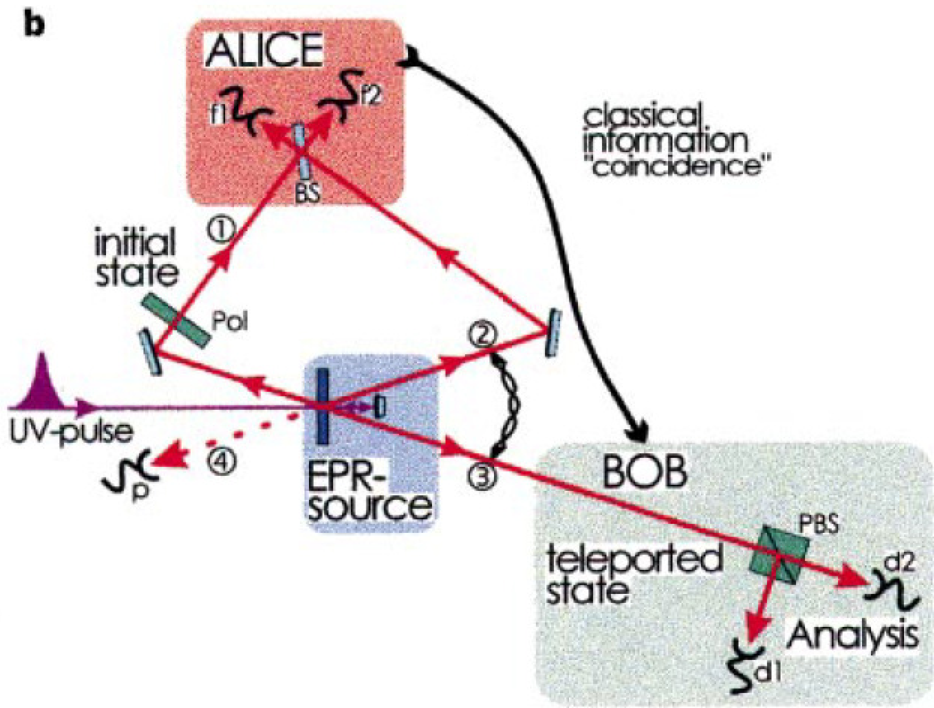
In a nonlinear crystal (beta barium borate, BBO) one UV photon produces two red photons, one vertically and one horizontally polarized.

At the intersection points:
Polarizations undefined, but have to be different.
→ Entangled Bell state

$$|\psi^-\rangle_{23} = \frac{1}{\sqrt{2}}\left(|\leftrightarrow\rangle_2 |\updownarrow\rangle_3 - |\updownarrow\rangle_2 |\leftrightarrow\rangle_3\right)$$

Creation of the States

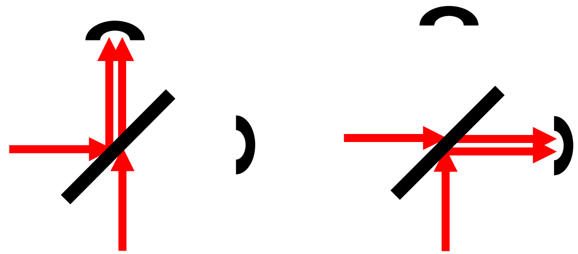
- UV pulse passes first time through crystal and produces entangled pair 2 & 3.
- Gets reflected and passes crystal again, produces again two photons.
- One of them is prepared to the state to be teleported, photon 1.
- The other, photon 4, indicates „photon 1 is on its way“.



Alice's Bell Measurement

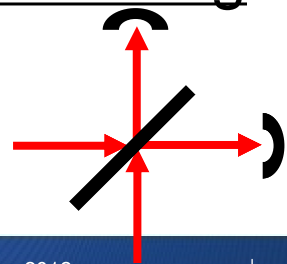
- Make photons 1 & 2 indistinguishable by superposition at beam splitter.
- Symmetric Bell states lead to <u>bunching</u>.
  → only one detector clicks

$$
\begin{aligned}
|\psi^+\rangle_{23} &= \frac{1}{\sqrt{2}}\left(|\leftrightarrow\rangle_2 |\updownarrow\rangle_3 + |\updownarrow\rangle_2 |\leftrightarrow\rangle_3\right) \\
|\phi^+\rangle_{23} &= \frac{1}{\sqrt{2}}\left(|\leftrightarrow\rangle_2 |\leftrightarrow\rangle_3 + |\updownarrow\rangle_2 |\updownarrow\rangle_3\right) \\
|\phi^-\rangle_{23} &= \frac{1}{\sqrt{2}}\left(|\leftrightarrow\rangle_2 |\leftrightarrow\rangle_3 - |\updownarrow\rangle_2 |\updownarrow\rangle_3\right)
\end{aligned}
$$



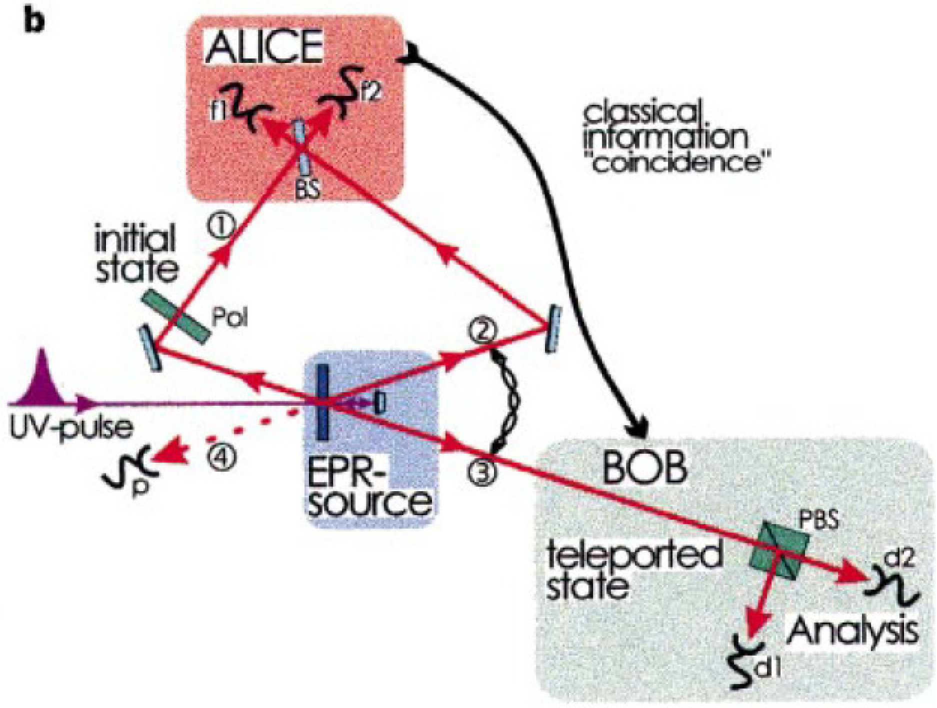
- Antisymmetric Bell state leads to <u>anti-bunching</u>.
  → coincidence measurement

$$|\psi^-\rangle_{12} = \frac{1}{\sqrt{2}}\left(|\leftrightarrow\rangle_1 |\updownarrow\rangle_2 - |\updownarrow\rangle_1 |\leftrightarrow\rangle_2\right)$$



Experimental Verification of Teleportation

- If coincidence pf1f2 : Alice tells Bob over classical channel „Teleportation successful".
- Show that teleportation works for basis, but NOT for preferred directions ↔ and ↕.
  → use -45° and 45°
- Bob measures with polarizing beam splitter:
  -45° : only d1 clicks
  45° : only d2 clicks
- Also measured 0°, 90° and circularly polarized.



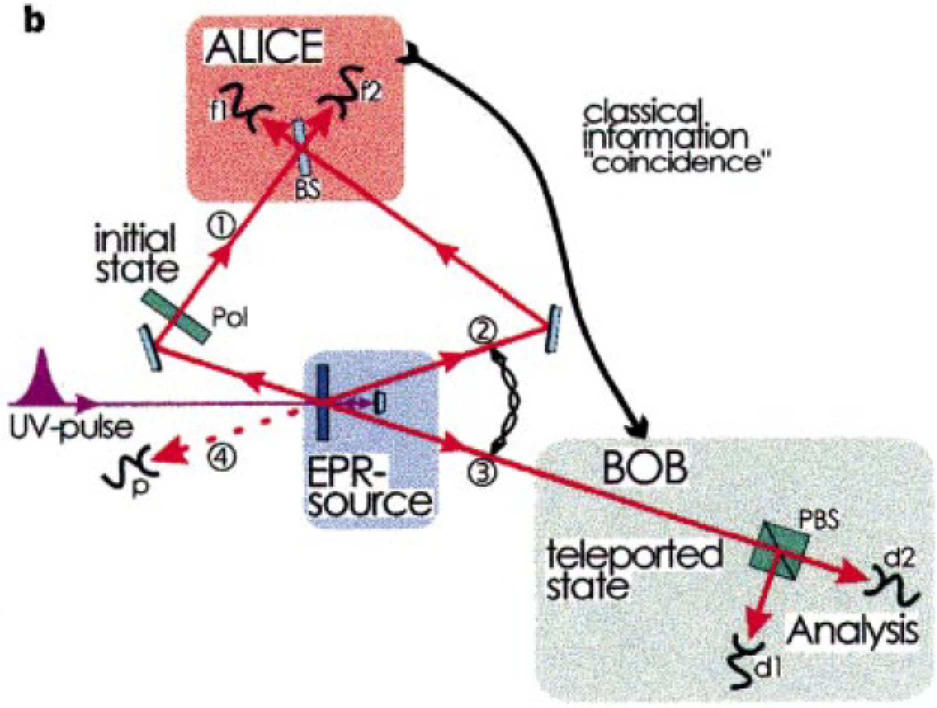
Results

- First experiment:
  photon 1 polarized at 45°

  Teleportation as soon as $|\psi^-\rangle_{12}$ detected
  ↔ f1f2 coincidence

  → photon 3 polarized at 45°

  Proof of teleportation:
  d1f1f2 and no d2f1f2 recording



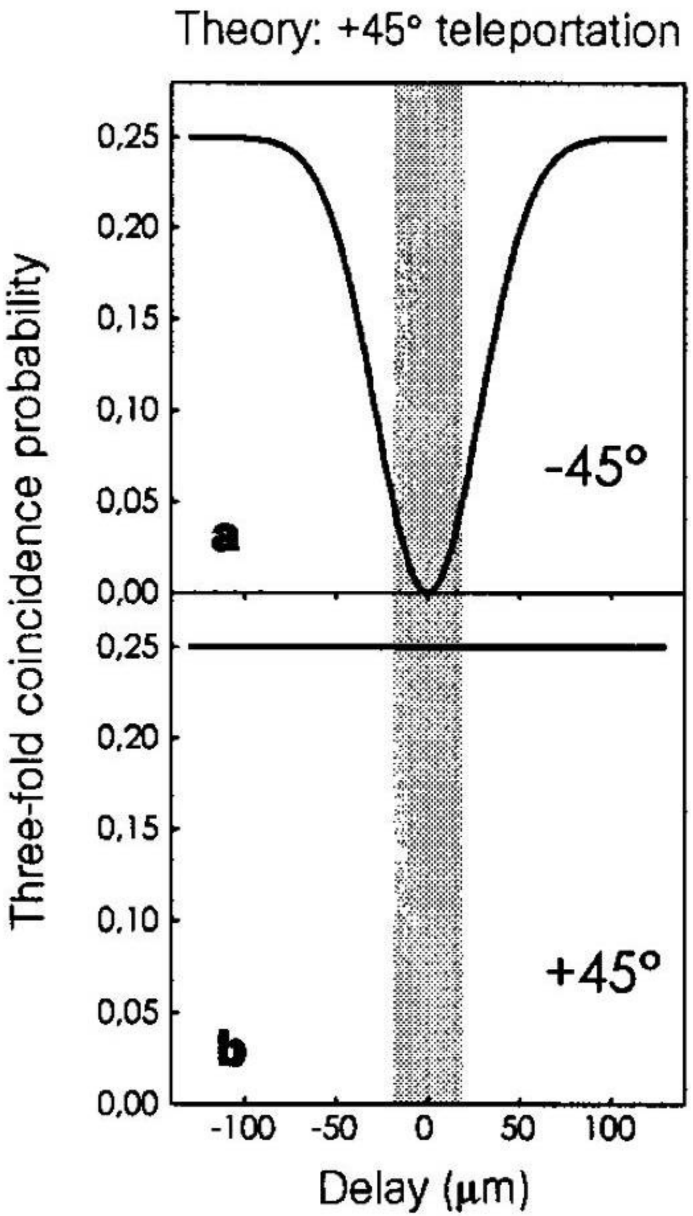
Temporal Overlap

- Changing delay between arrival times of photons 1 & 2 by translating the retroflection mirror

- Out of teleportation region:

f1f2 coincidence: 50%
d1, d2: 50%

→ d1f1f2: 25% +45°
→ d2f1f2: 25% -45°

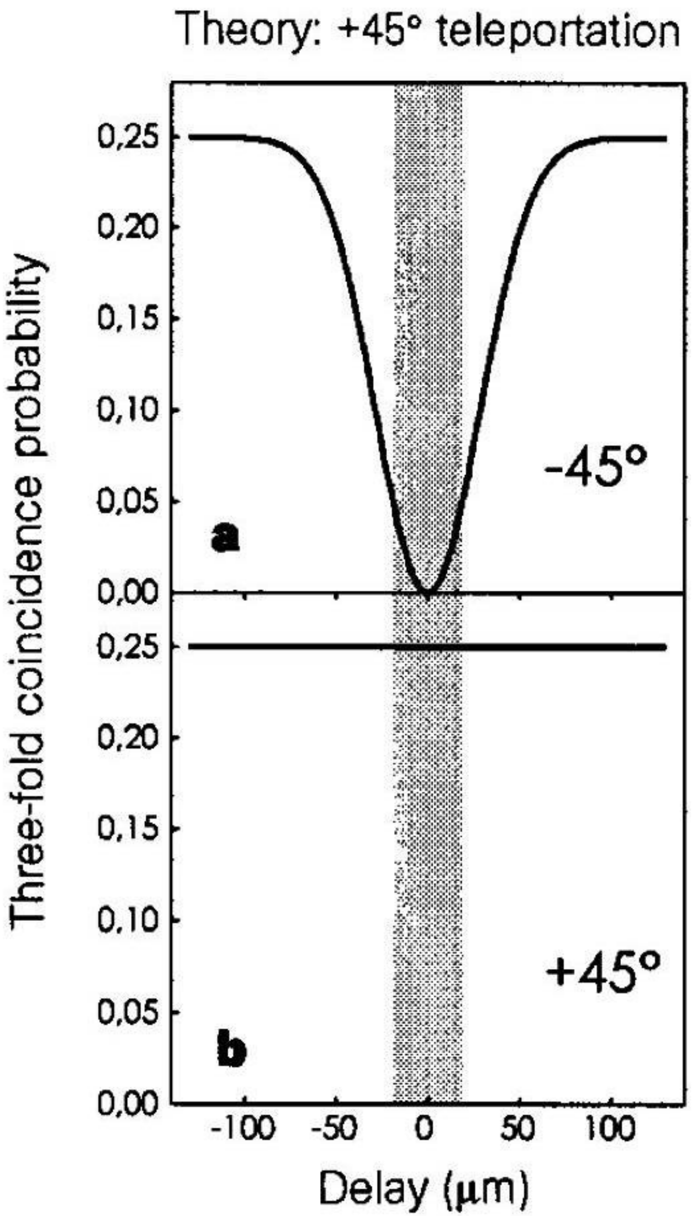


Temporal Overlap

- At zero delay:
  f1f2 coincidence: 25%
  (only if $|\psi^-\rangle_{12}$ state)

  - without teleportation
    d1, d2: 50%
    → d1f1f2: 12.5% $+45^\circ$
    → d2f1f2: 12.5% -45°

  - with teleportation
    d1: 100% → d1f1f2: 25% $+45^\circ$
    d2: 0% → d2f1f2: 0% -45°



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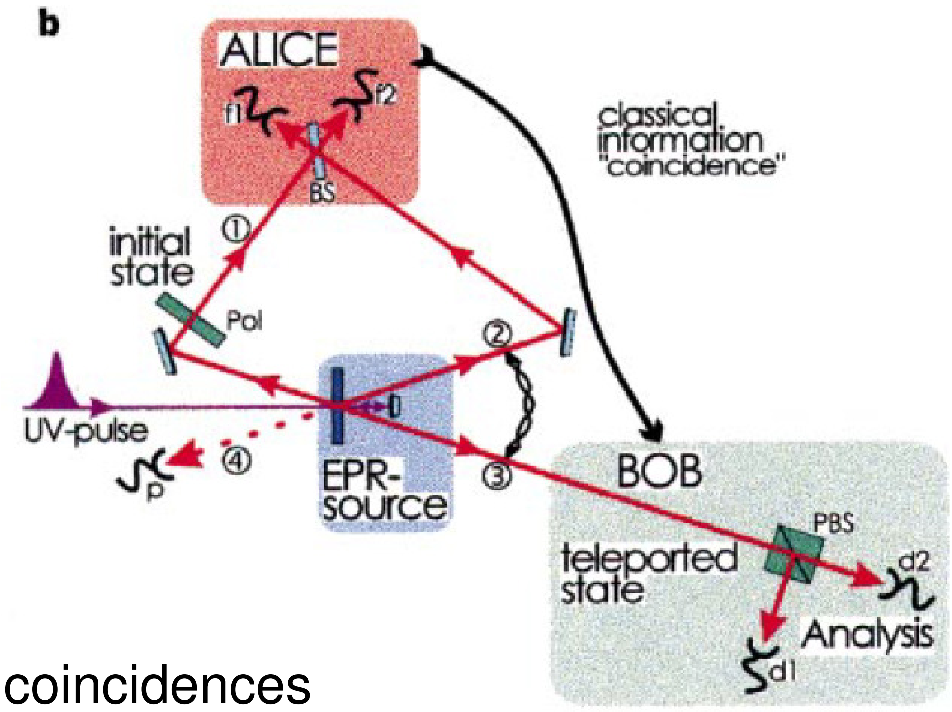
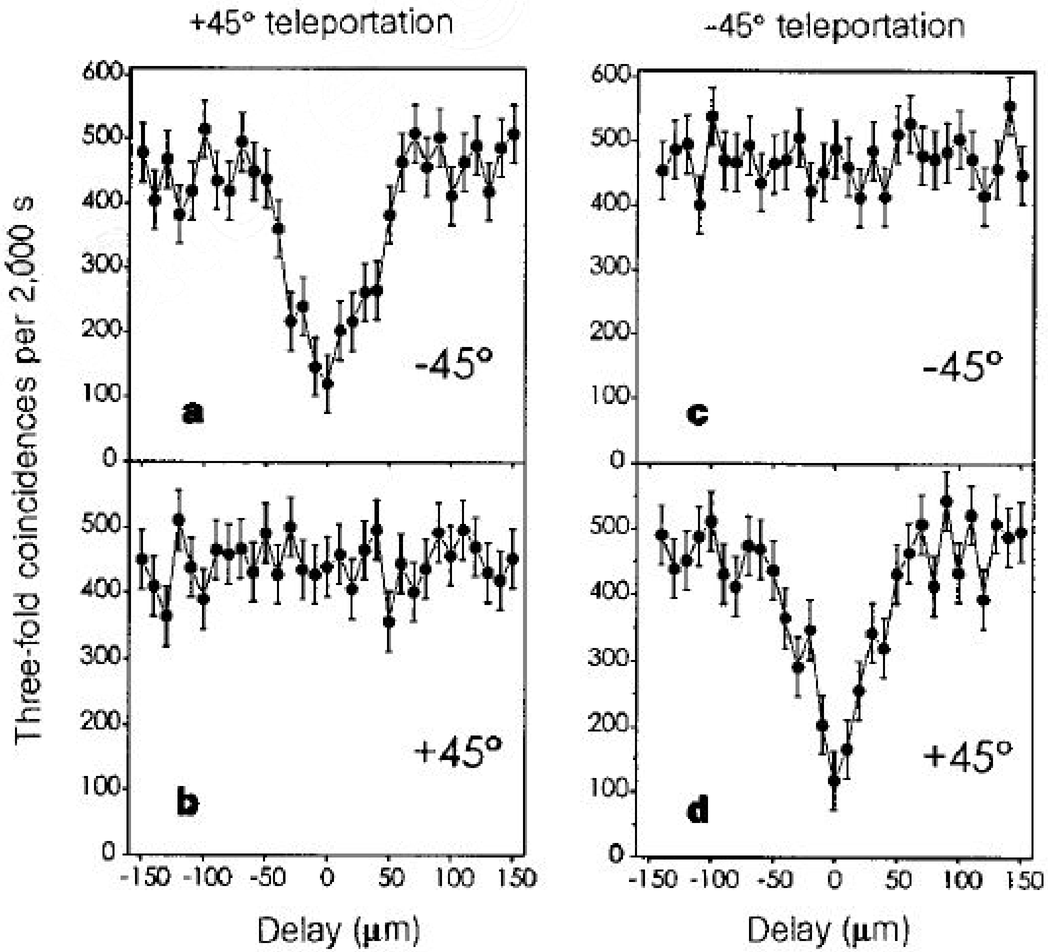
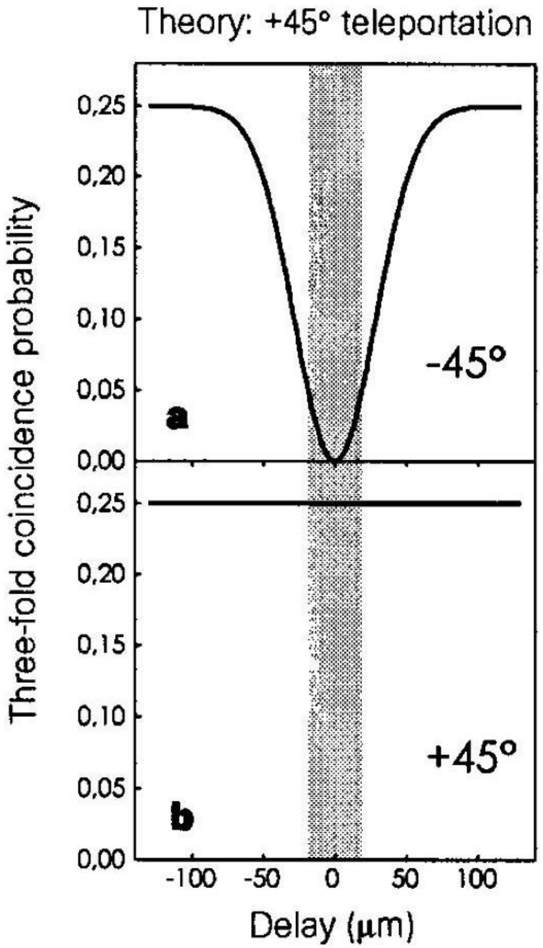
Spurious three-fold coincidences

- Emission of two pairs of down-converted photons by a single source
- Significant contribution to the three-fold coincidence rates
- Indentified by blocking the path of photon 1
- Experim. determined value: 68% ±1% of spurious three-fold coincidences



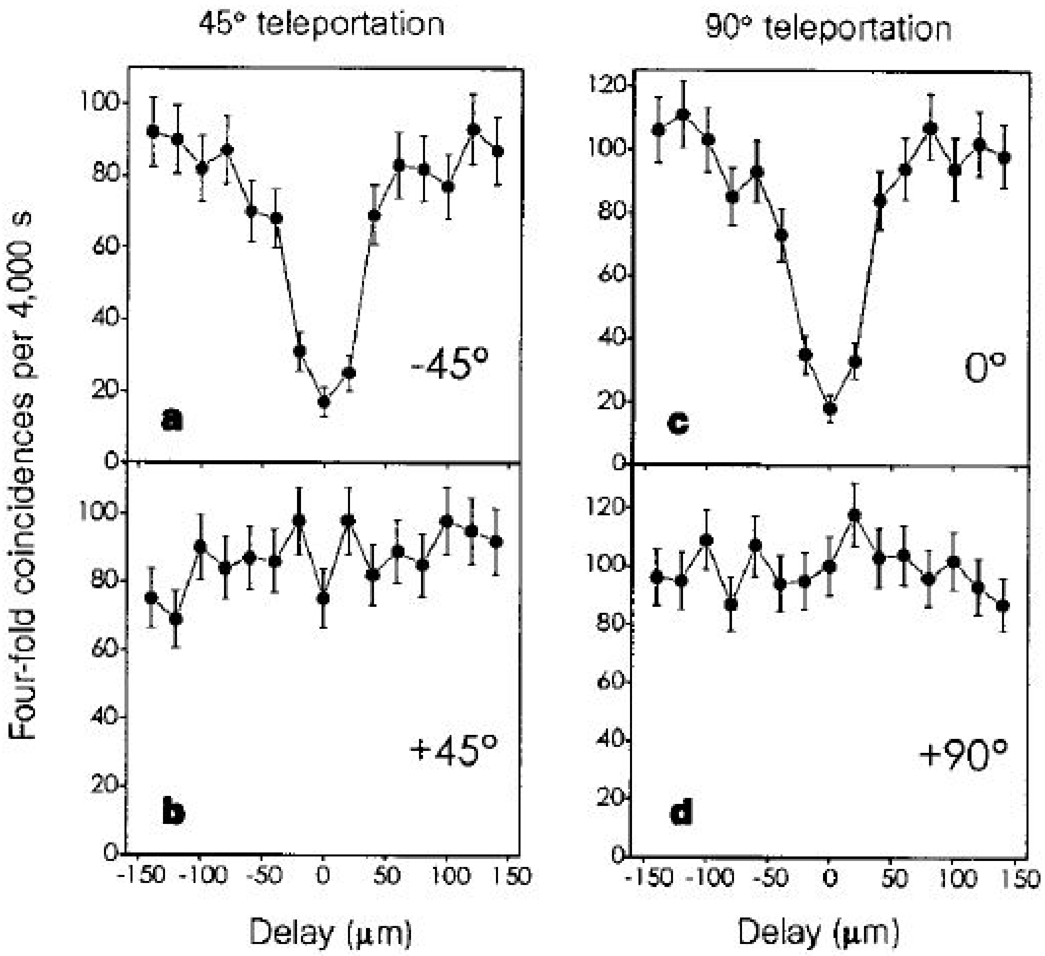
Experimental Results





- Spurious three-fold coincidence contribution subtracted

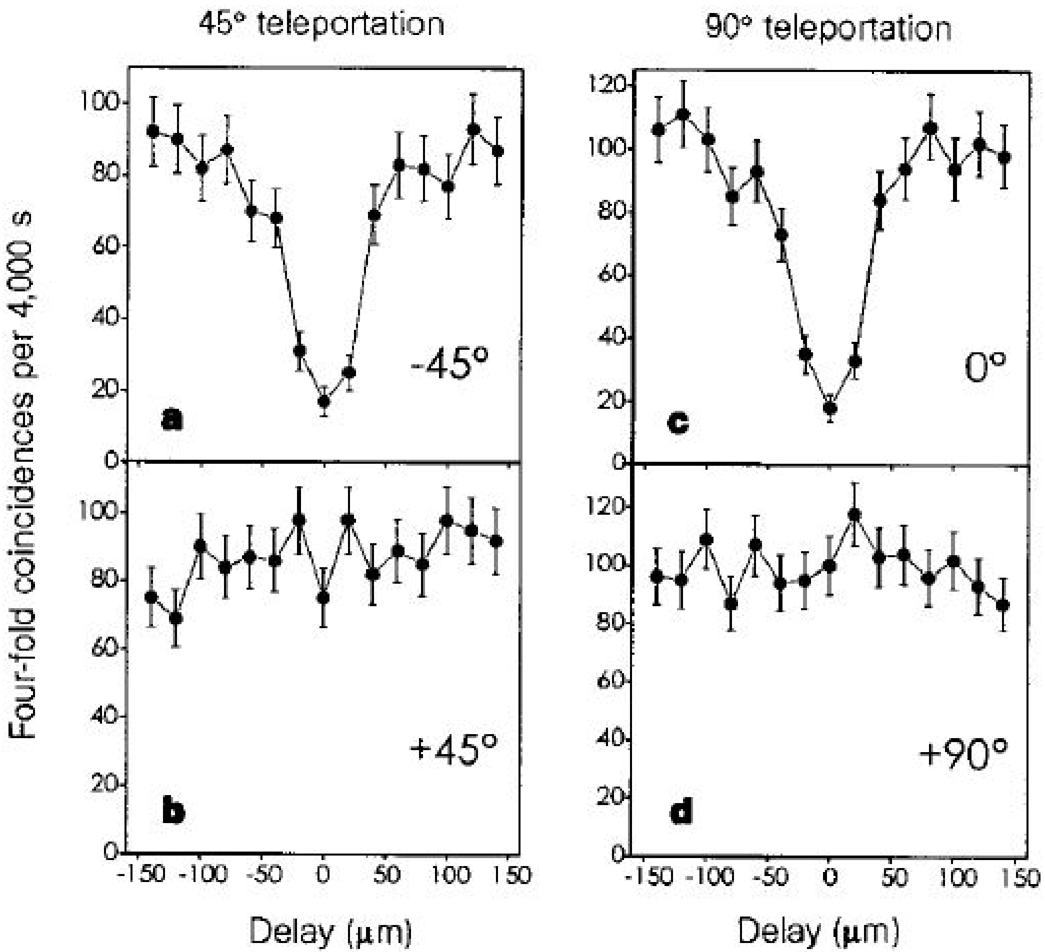
Experimental Results



- Four-fold coincidence:
  pd1f1f2
  p: detection of photon 4

→ no spurious three-fold coincidence background needs to be subtracted

Experimental Results



- Visibilities of the dips: 70% ± 3%

= degree of polarization of the teleported photon in the right state

→ Proof that they have demonstrated the teleportation of the quantum state of a single photon

Outlook

- Entangling photons with atoms, phonons with ions etc.
- Would allow to transfer the state of fast-decohering, short–lived particles onto some more stable systems.
- Quantum memories: information of incoming photons stored on trapped ions
- Preserving quantum states in a hostile environment: great advantages in the realm of quantum computation
- Teleportation could provide links between quantum computers.

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Questions?