Experimental Quantum Teleportation

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ETHZ

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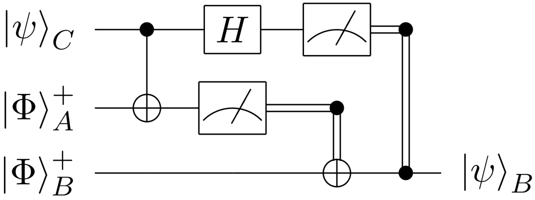
Table of Contents

Bell States

$$|\Phi^{+}\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right)$$
$$|\Phi^{-}\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle - |11\rangle\right)$$
$$|\psi_{+}\rangle = \frac{1}{\sqrt{2}}\left(|10\rangle + |01\rangle\right)$$
$$|\psi^{-}\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle - |10\rangle\right)$$

Teleportation Algorithm

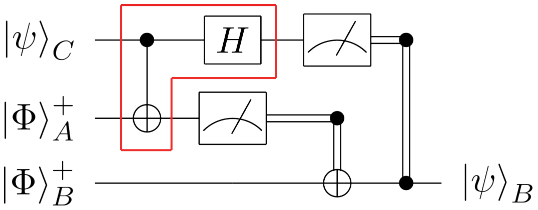


Input state: $|\psi_0\rangle = |\psi\rangle_C \otimes |\Phi^+\rangle$

$|\psi\rangle_C = \alpha\,|0\rangle + \beta\,|1\rangle$ State to be teleported

$|\Phi^+\rangle = \frac{1}{\sqrt{2}}\left(|0_A 0_B\rangle + |1_A 1_B\rangle\right)$ Entangled Bell State pair

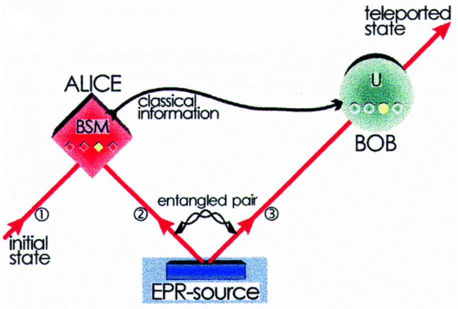
Teleportation Algorithm



- Alice performs CNOT + Hadamard gate to her 2 qubits

$$=> \ |\psi_0'\rangle = \frac{1}{2}\Big[|00\rangle(\alpha|0\rangle + \beta|1\rangle) + |01\rangle(\alpha|1\rangle + \beta|0\rangle) + |10\rangle(\alpha|0\rangle - \beta|1\rangle) + |11\rangle(\alpha|1\rangle - \beta|0\rangle)\Big]$$

- If Alice measures $|00\rangle$, Bob's qubit is projected to $|\psi_B\rangle = (\alpha|0\rangle + \beta|1\rangle)$ $=> |\psi\rangle$ has been quantum teleported!



- How to produce an entangled pair (PDC)?
- How to make a Bell State Measurement (BSM) for Alice?
- How to design a polarization measurement for Bob?

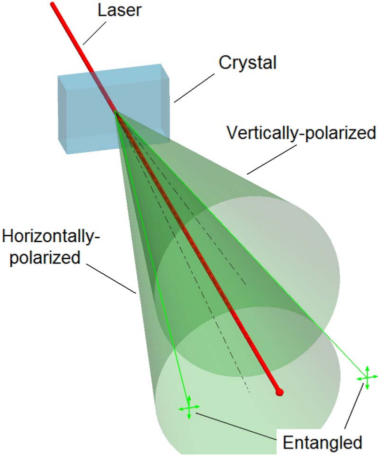
"Experimental quantum teleportation"

Dik Bouwmeester, Jian-Wei Pan, Klaus Mattle, Manfred Eibl, Harald Weinfurter and Anton Zeilinger
Nature **390** Dezember 1997

Photon properties:

- 2-dim property: polarization
- mobile
- known techniques to create entangled states and conduct Bell State Measurements

Production: Parametric Down Conversion (type II)

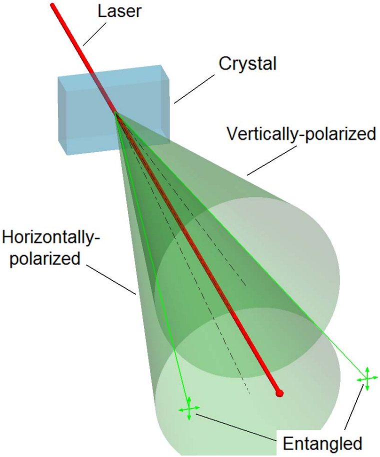


Source: Wikipedia

- nonlinear crystal
- vacuum fluctuations
- undetermined polarization on cone intersections

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

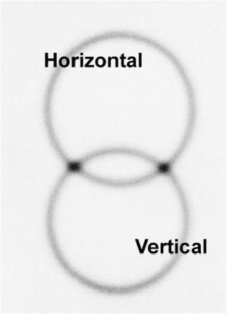
Production: Parametric Down Conversion (type II)



Source: Wikipedia

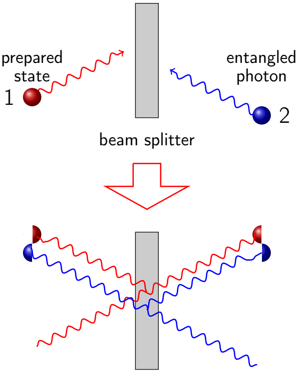
$$|\psi^-\rangle_{12} = \frac{1}{\sqrt{2}} \left(|\leftrightarrow\rangle_1 |\updownarrow\rangle_2 - |\updownarrow\rangle_1 |\leftrightarrow\rangle_2 \right)$$

"EPR-source"



Simultanous Detection on Both Sides of Beam Splitter

Anti-bunching:



Input state:

- symmetric
  → reflection and transmission interfere deconstructively
- antisymmetric
  → constructive interference

simoultaneous detection
⇒ antisymmetric input state

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

Projection on Bell State

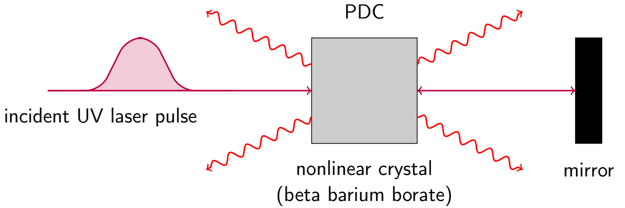
Coherence Time

Length of laser pulse:	200 fs
Wavelength:	788 nm
Bandwidth:	4 nm

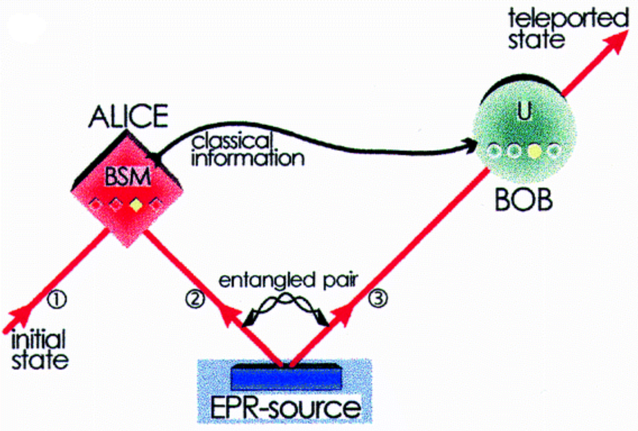
$$\Delta \mathrm{E} \cdot \Delta \mathrm{t} \geq \hbar/2$$

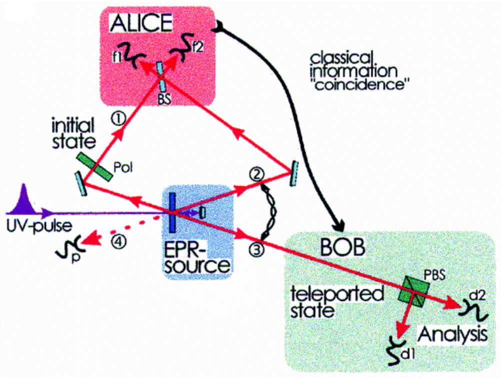
$\Rightarrow$ coherence time: 520 fs

time difference $\leq$ 500 fs
$\Leftrightarrow$ "simultanous"

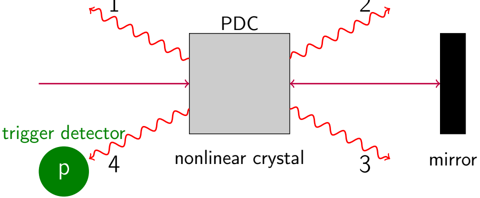


Experimental Setup

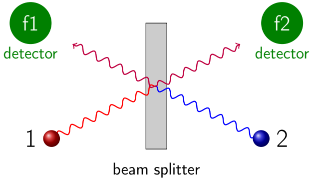




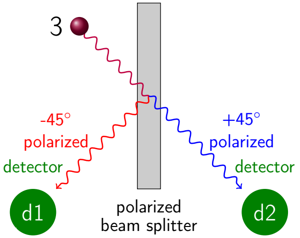
EPR-Source:

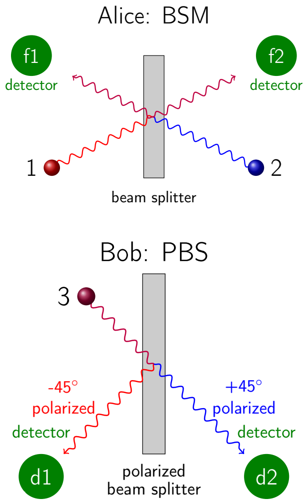


Alice: BSM



Bob: PBS

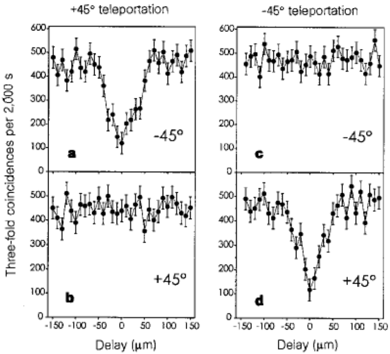




Preparation of photon 1 in $+45^\circ$ state:

- f1 & f2 detect $|\psi^-\rangle_{12}$ by recording a coincidence in 25% of all cases
- If coincidence f1f2 clicks:
- => photon 3 should be also polarized at $+45^\circ$
- => only d2 at $+45^\circ$ should click
- Proof that polarization of photon 1 has been teleported to photon 3: *coincidence f1f2d2* ($+45^\circ$) and *absence of f1f2d1* (-45°)

Experimental Results



Outside region of teleportation:

- photon 1 and 2 independant => prob 50% of coincidence f1f2
- photon 3 not well defined polarization => d1 and d2 both prob 50% of click

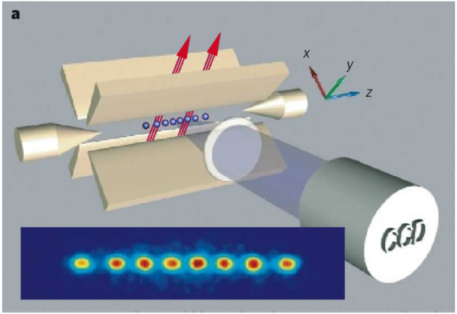
=> prob 25% for f1f2d1,
25% for f1f2d2

Inside region of teleportation:

- prob 25% for $+45°$ polarization
- prob 0% for $-45°$ polarization

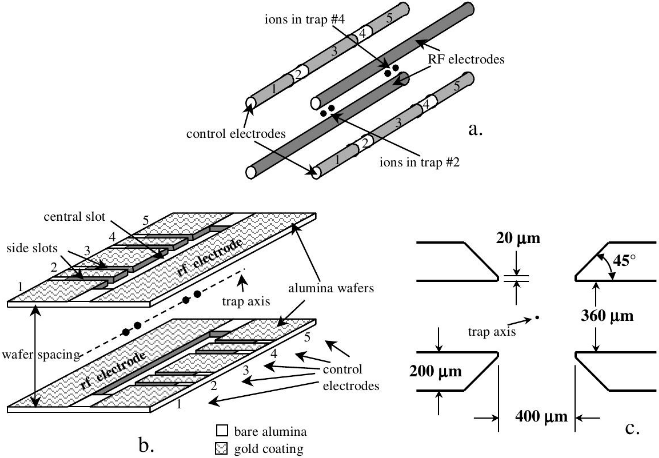
“Deterministic quantum teleportation of atomic qubits”

M. D. Barrett, J. Chiaverini, T. Schaetz, J. Britton, W. M. Itano, J. D. Jost,
E. Knill, C. Langer, D. Leibfried, R. Ozeri & D. J. Wineland
Nature **429** July 2004



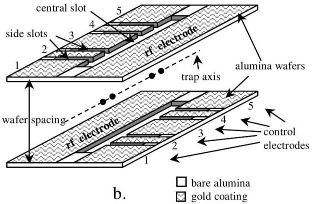
R. Blatt & D. Winehouse, Nature **453** 2008

Realization of an Ion Trap



Source: Transport of Quantum States and Separation of Ions in a dual RF Trap, Rowe et al, Quantum Information and Computation, Vol. 2, No. 4 (2002)

Trap used for Teleportation



Trap of similar design

Source: Transport of Quantum States and Separation of Ions in a dual RF Trap, Rowe et al, Quantum Information and Computation, Vol. 2, No. 4 (2002)

Teleportation trap specifications:

- 8 electrodes
- ions: $^{9}\mathrm{Be}^{+}$
- qubit: groundstate hyperfine levels
  $|\uparrow\rangle \equiv |F = 1, m = -1\rangle$
  $|\downarrow\rangle \equiv |F = 2, m = -2\rangle$
- transition frequency:
  $\nu = 1.25$ GHz

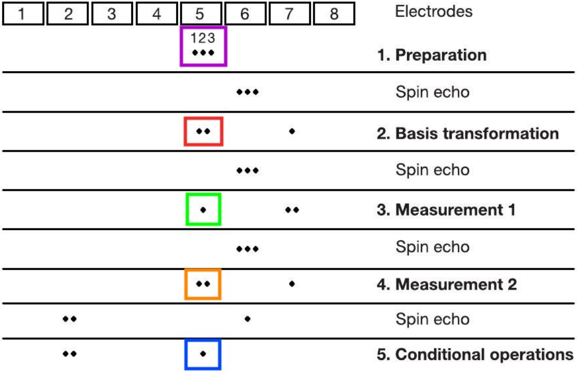
Capabilities of this Layout:

- control movement of single ions
- two laser beams: Single-qubit *rotations* & two qubit *phase* gate
- preparation of ion #2 in any state via $|S\rangle_{1,3} \otimes |\downarrow\rangle_2$:

$$|S\rangle_{1,3} := \frac{1}{\sqrt{2}} \left(|\uparrow\rangle_1 |\downarrow\rangle_3 - |\downarrow\rangle_1 |\uparrow\rangle_3 \right)$$

Rotation $\rightarrow$ Input state $|\psi\rangle = |S\rangle_{1,3} \otimes \mathrm{R}(\phi) |\downarrow\rangle_2$

- readout of single ions using *resonance fluorescence*



Preparation:

$|\psi\rangle = |S\rangle_{1,3} \otimes |\downarrow\rangle_2$

then rotate by ϕ

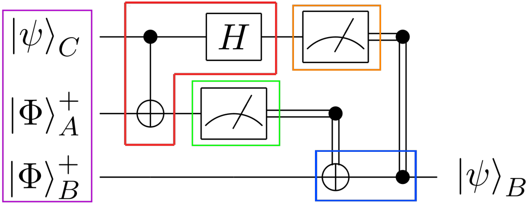
$\Rightarrow |\psi\rangle_2 = \alpha\,|\downarrow\rangle + \beta\,|\uparrow\rangle$

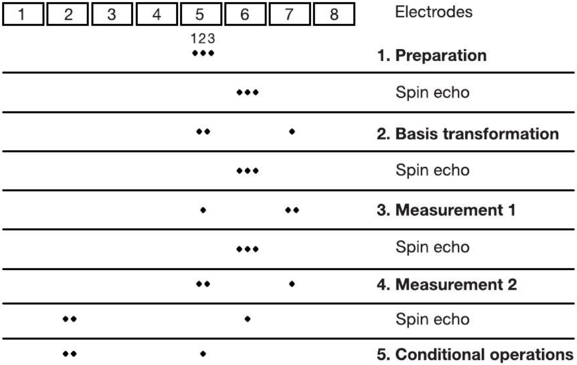
Detection:

resonance fluorescence

$|\downarrow\rangle$ fluoresces

$|\uparrow\rangle$ no response





Preparation:

$|\psi\rangle = |S\rangle_{1,3} \otimes |\downarrow\rangle_2$

then rotate by ϕ

$\Rightarrow |\psi\rangle_2 = \alpha |\downarrow\rangle + \beta |\uparrow\rangle$

Detection:

resonance fluorescence

$|\downarrow\rangle$ fluoresces

$|\uparrow\rangle$ no response

achieved fidelities for ground states:

$$|\downarrow\rangle : \quad 84 \pm 2\%$$

$$|\uparrow\rangle : \quad 78 \pm 2\%$$

Conclusions

- teleportation of a single photon and single ion state
- only for quantum-scale particles
- not faster than light
- Photon exp: only 25% of time
- Next: transfer fast-decohering particle-states onto stable system
  $\rightarrow$ quantum memories and quantum computing
- State of the art: no photon BSM with $\geq$ 50% success rate