Early Quantum Information

"The uncertainty principle imposes restrictions on the capacity of certain types of communication channels…In compensation for this 'quantum noise', quantum mechanics allows us novel forms of coding without analogue in communication channels adequately described by classical physics."

--Steven Wiesner,
sewing the seeds for quantum
communication in 1969;
appeared 1983

Quantum superdense coding

PHYSICAL REVIEW
LETTERS

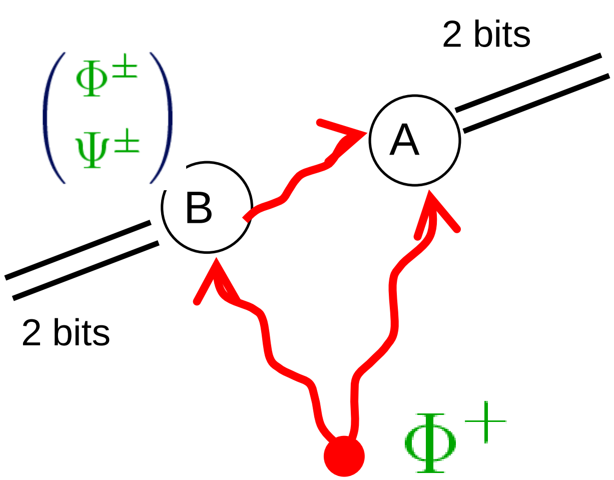
VOLUME 69 | 16 NOVEMBER 1992 | NUMBER 20

Communication via One- and Two-Particle Operators on Einstein-Podolsky-Rosen States

Charles H. Bennett
IBM Research Division, T. J. Watson Research Center, Yorktown Heights, New York 10598

Stephen J. Wiesner
74 Parkman Street, Brookline, Massachusetts 02146

(Received 16 June 1992)



✓ 1 entangled photon each to Bob and Alice

✓ Bob applies one of 4 U's ➠ one of the 4 Bell states; sends photon to Alice

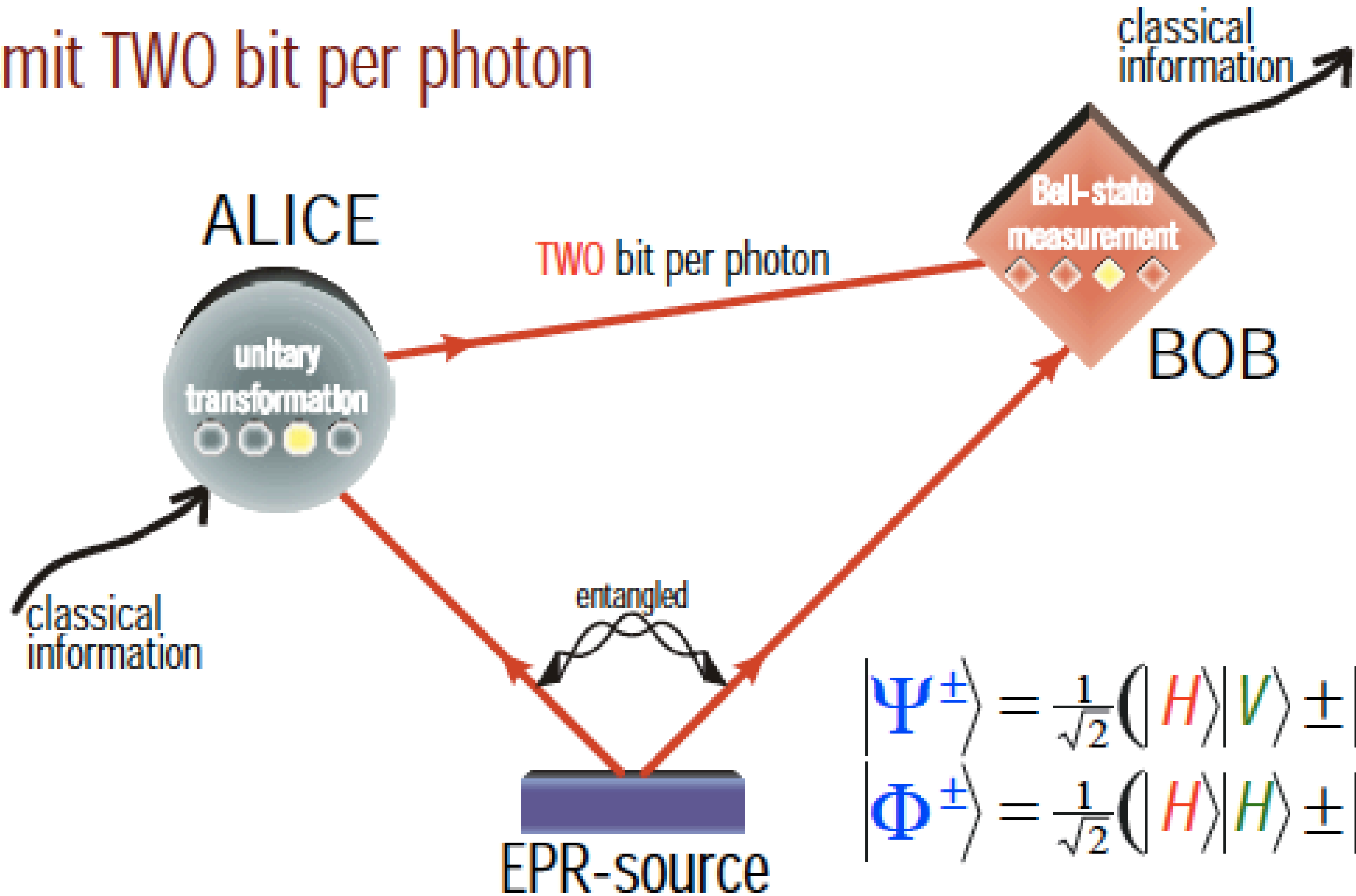
✓ Alice: BSA ➠ infer one of 4 messages

Channel cap. = $\log_2 4$ = 2 bits/photon_from_Bob

Quantum Dense Coding

C.H. Bennett, S. Wiesner PRL

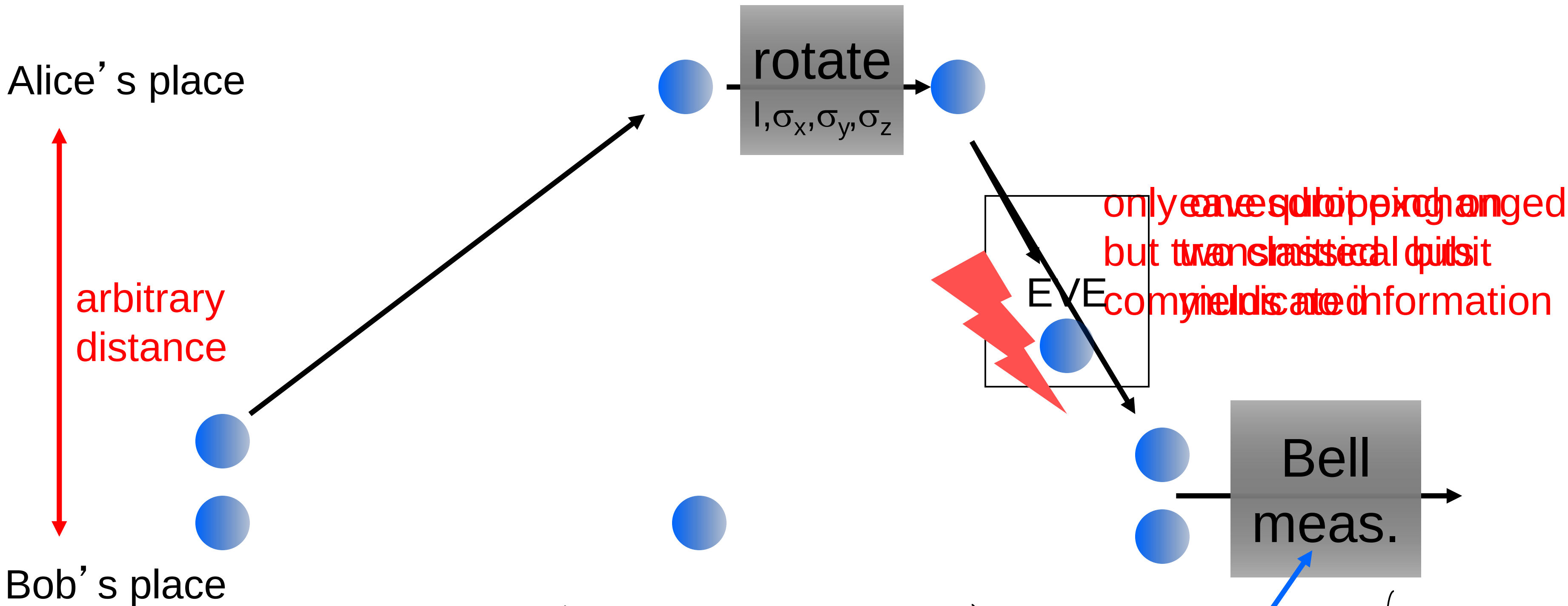
transmit TWO bit per photon



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

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

Quantum dense coding



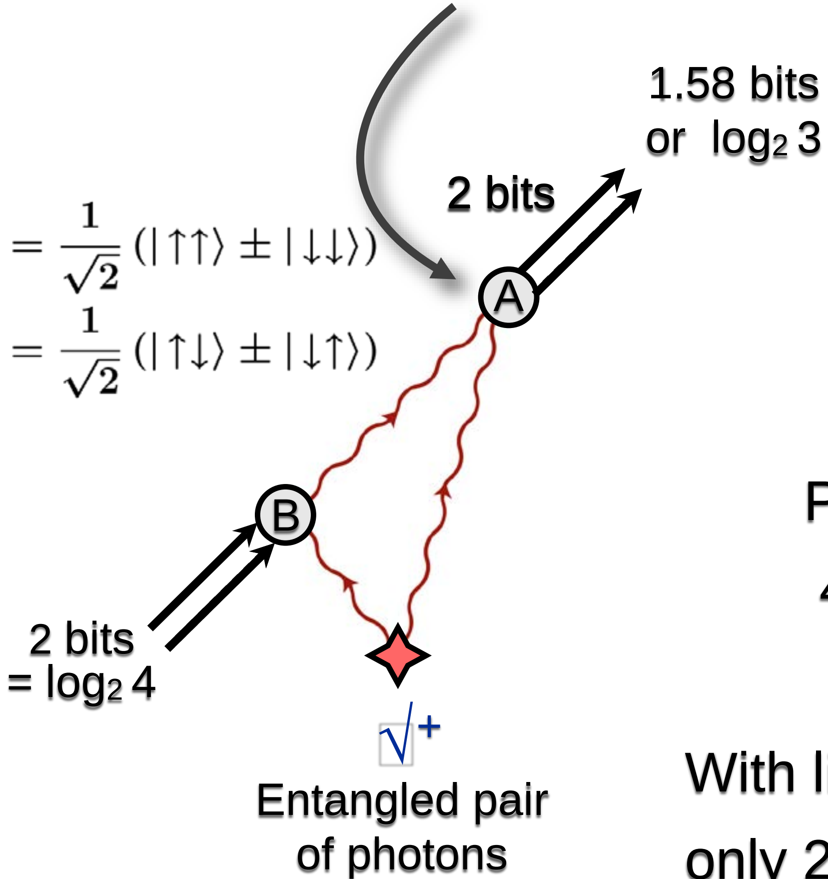
$$\frac{1}{\sqrt{2}}(|\downarrow\rangle_A|\downarrow\rangle_B + |\uparrow\rangle_A|\uparrow\rangle_B)$$

$$\left.\begin{aligned}
\hat{I}^A &: \quad \frac{1}{\sqrt{2}}(|\downarrow\rangle_A|\downarrow\rangle_B + |\uparrow\rangle_A|\uparrow\rangle_B) \\
\hat{\sigma}_x^A &: \quad \frac{1}{\sqrt{2}}(|\uparrow\rangle_A|\downarrow\rangle_B + |\downarrow\rangle_A|\uparrow\rangle_B) \\
\hat{\sigma}_y^A &: \quad \frac{-i}{\sqrt{2}}(|\uparrow\rangle_A|\downarrow\rangle_B - |\downarrow\rangle_A|\uparrow\rangle_B) \\
\hat{\sigma}_z^A &: \quad \frac{1}{\sqrt{2}}(|\downarrow\rangle_A|\downarrow\rangle_B - |\uparrow\rangle_A|\uparrow\rangle_B)
\end{aligned}\right\} \text{CNOT}^{AB} \cdot (-\frac{\pi}{2})_x^A \otimes \hat{I}^B \left\{\begin{aligned}
&|\uparrow\rangle_A|\uparrow\rangle_B \\
&|\uparrow\rangle_A|\downarrow\rangle_B \\
&|\downarrow\rangle_A|\downarrow\rangle_B \\
&|\downarrow\rangle_A|\uparrow\rangle_B
\end{aligned}\right.$$

In the original dense coding protocol[1] Alice needs Bell-state analysis, however...

$$\Phi^{\pm} = \frac{1}{\sqrt{2}}(|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle)$$

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



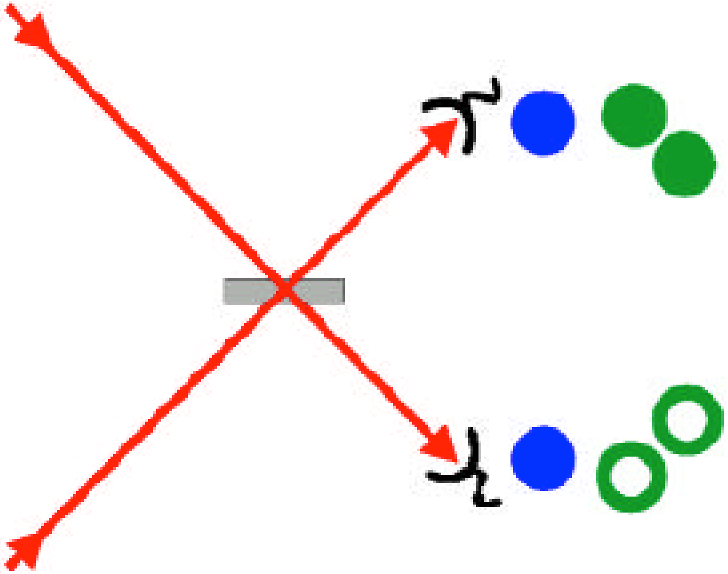
Photon-photon interactions are inefficient in practice[2] $\sim 10^{-9}$

Probabilistic schemes ineff. too[3]
4 out of 4, at most 50% efficient

With linear optics and CC, **Impossible**[4]
only 2 Bell states discriminated
for a 3-message encoding

[1] Bennett/Wiesner (1992) [2] Kim et al. (2001) [3] Vaidman/Noran (1999), Lutkenhaus et al. (1999)
[4] Calsamiglia/Lutkenhaus (1999)

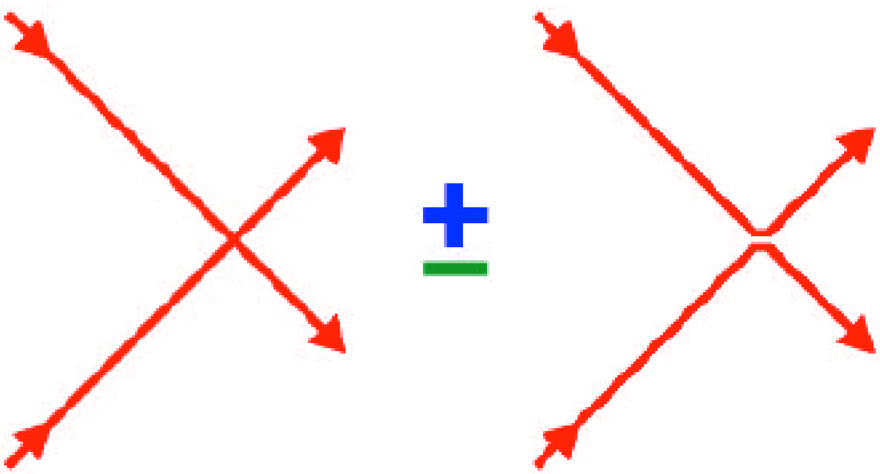
Two-particle interference at a beamsplitter



Fermions

Coincidence

(anti-symmetric wave func



Bosons

Anti-coincidence

(symmetric wave function)

Ψ^- anti-symmetric ➔ "Fermion"

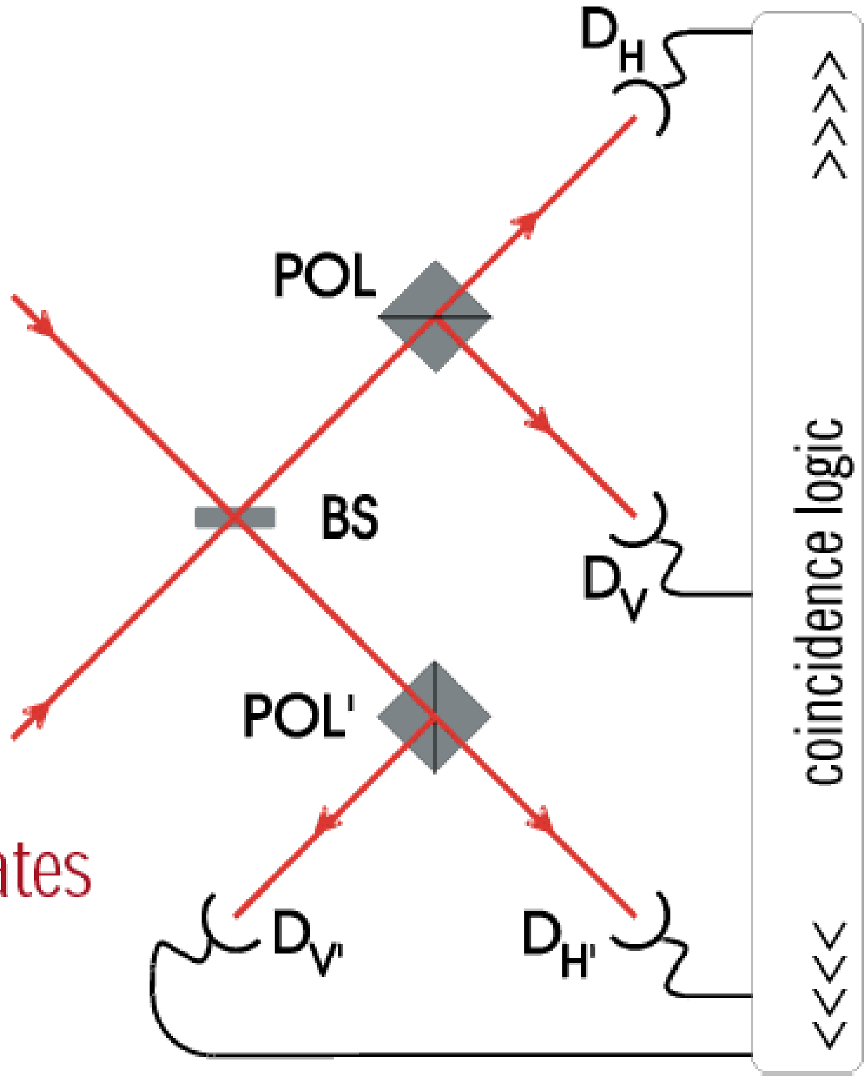
$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle|V\rangle - |V\rangle|H\rangle\right)$$

$\Psi^+, \Phi^\pm$ symmetric ➔ "Boson"

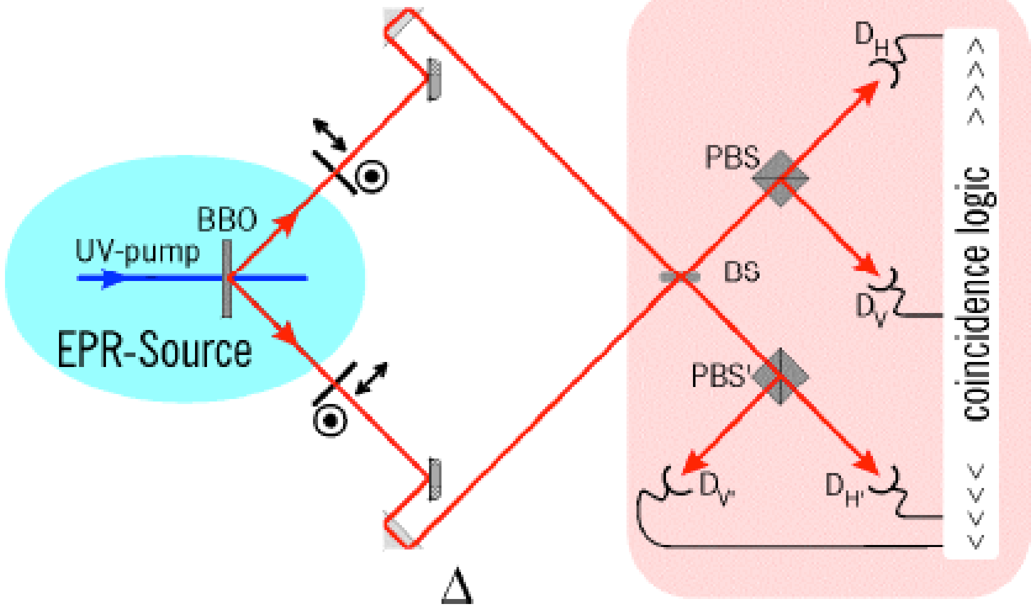
$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle|V\rangle + |V\rangle|H\rangle\right)$$

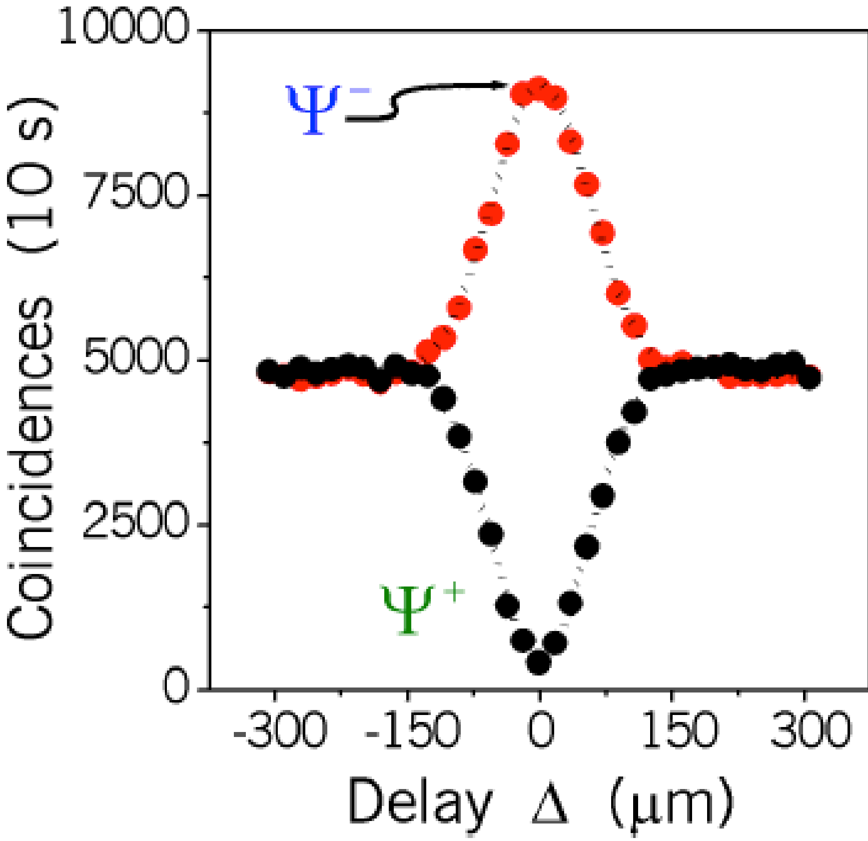
$$|\Phi^\pm\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle|H\rangle \pm |V\rangle|V\rangle\right)$$

➔ identify TWO of the four Bell-states



Distinguish Bell-states





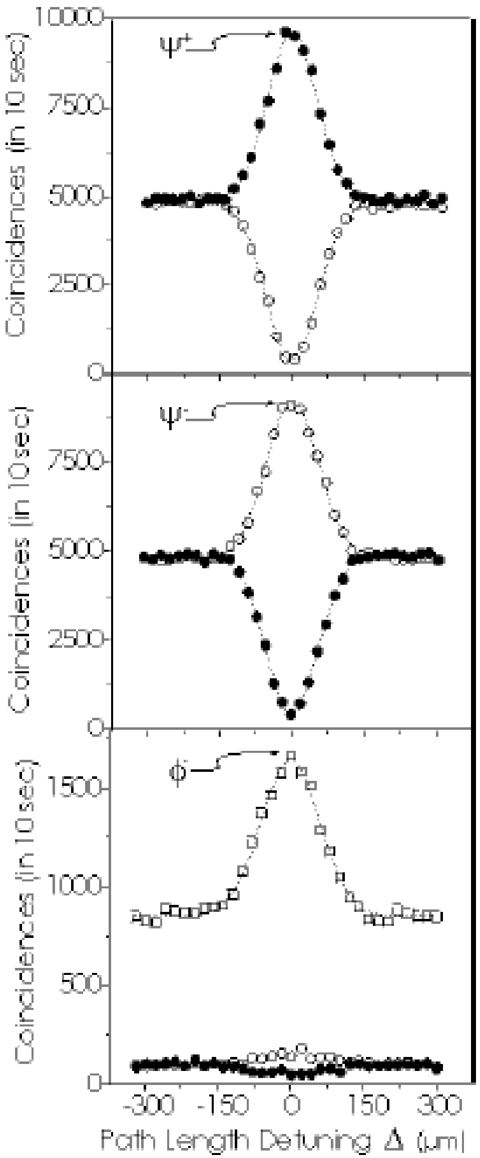
Coincidence rate behind beamsplitter

maximum for Ψ^-

minimum for Ψ^+

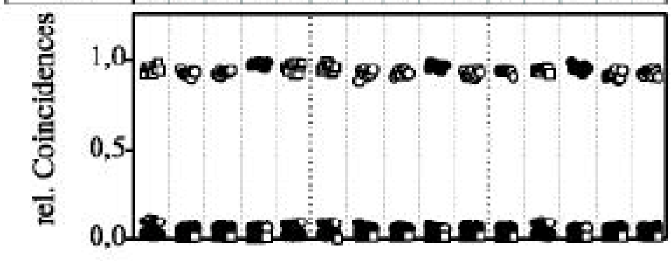
Quantum Dense Coding

K. Mattle, H. Weinfurter, P.G. Kwiat, A. Zeilinger, Phys. Rev. Lett. **76**, 4656 (1996)

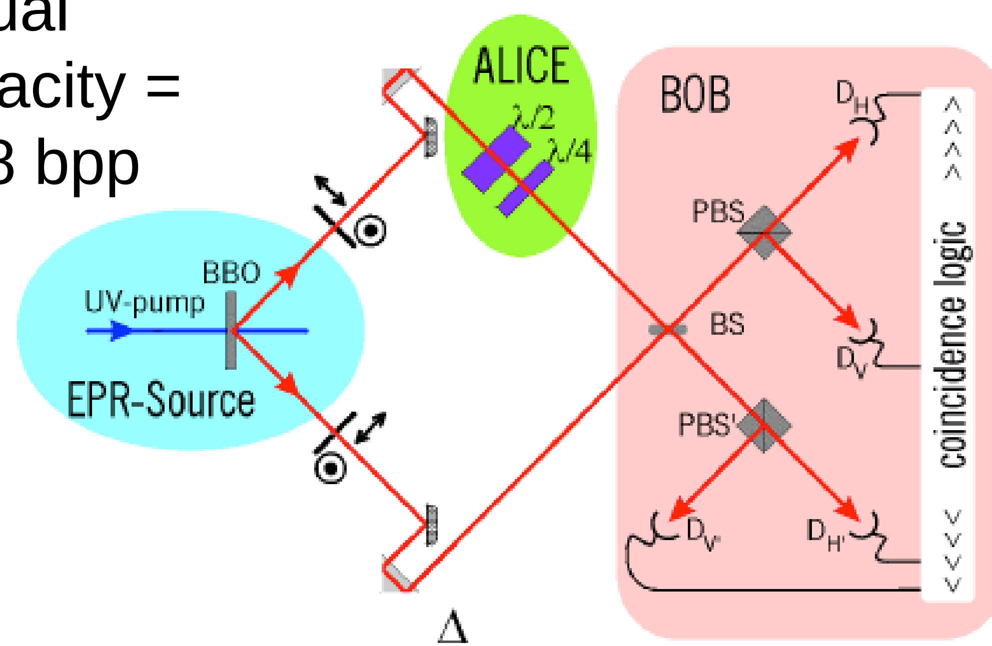


- 3 possible manipulations
- communicate "trits"
- capacity 1.58 bit/photon

Letter	K					M					°				
ASCII-code	75					77					179				
trit	0	2	2	1	0	0	2	2	1	2	2	0	1	2	2



Actual capacity = 1.18 bpp ☹



VOLUME 93, NUMBER 4 PHYSICAL REVIEW LETTERS week ending 23 JULY 2004

Quantum Dense Coding with Atomic Qubits

T. Schaetz, M. D. Barrett,* D. Leibfried, J. Chiaverini, J. Britton, W. M. Itano, J. D. Jost, C. Langer, and D. J. Wineland
Time and Frequency Division, NIST, Boulder, Colorado 80305-3328, USA
(Received 27 April 2004; published 22 July 2004)

We report the implementation of quantum dense coding on individual atomic qubits with the use of two trapped $^9Be^+$ ions. The protocol is implemented with a complete Bell measurement that distinguishes the four operations used to encode two bits of classical information. We measure an average transmission fidelity of 0.85(1) and determine a channel capacity of 1.16(1).

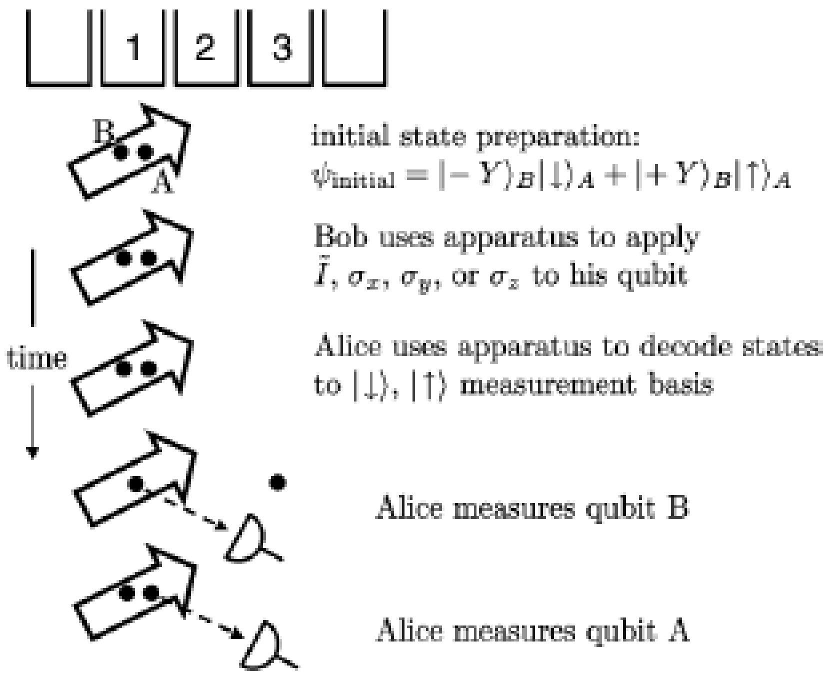


TABLE I. Correlations between Bob's applied operator (top row) and Alice's state measurements of both qubits (left column). The entries correspond to the probabilities measured by Alice for each basis state. Ideally, the entries in bold should equal 1 and all other entries should equal zero.

	$\tilde{I}$	σ_y	σ_z	σ_x
$\vert\downarrow\rangle_B\vert\downarrow\rangle_A$	**0.84(2)**	0.07(1)	0.08(1)	0.02(1)
$\vert\uparrow\rangle_B\vert\downarrow\rangle_A$	0.07(1)	0.01(1)	**0.84(1)**	0.04(1)
$\vert\downarrow\rangle_B\vert\uparrow\rangle_A$	0.06(1)	**0.84(1)**	0.04(1)	0.08(1)
$\vert\uparrow\rangle_B\vert\uparrow\rangle_A$	0.03(1)	0.08(1)	0.04(1)	**0.87(1)**

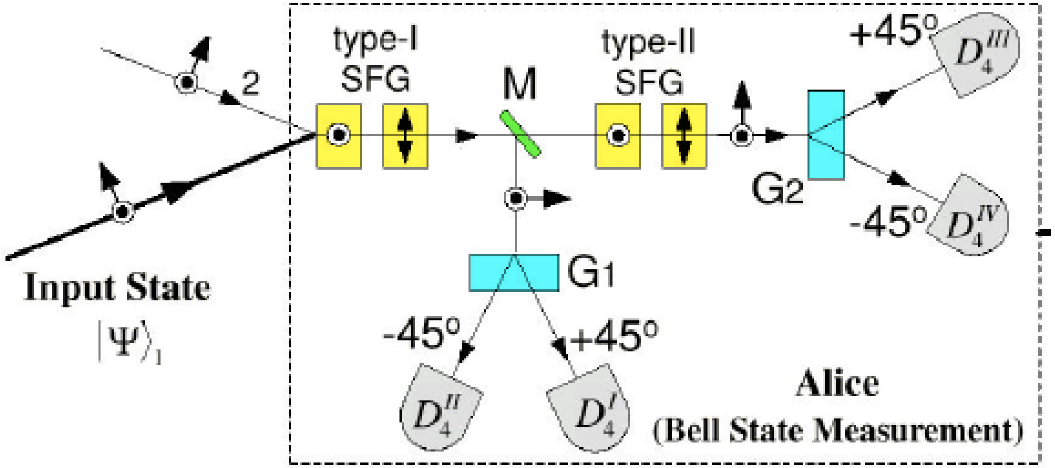
Average fidelity: 85%
→ CC = 1.16

VOLUME 86, NUMBER 7 PHYSICAL REVIEW LETTERS 12 FEBRUARY 2001

Quantum Teleportation of a Polarization State with a Complete Bell State Measurement

Yoon-Ho Kim,* Sergei P. Kulik,† and Yanhua Shih
Department of Physics, University of Maryland, Baltimore County, Baltimore, Maryland 21250
(Received 20 July 2000)

We report a quantum teleportation experiment in which nonlinear interactions are used for the Bell state measurements. The experimental results demonstrate the working principle of irreversibly teleporting an unknown arbitrary polarization state from one system to another distant system by disassembling into and then later reconstructing from purely classical information and nonclassical EPR correlations. The distinct feature of this experiment is that *all* four Bell states can be distinguished in the Bell state measurement. Teleportation of a polarization state can thus occur with certainty in principle.



Four SFG nonlinear crystals are used for "measuring" and "distinguishing" the complete set of the four Bell states. Photon 1 and photon 2 may interact either in the two type-I crystals or in the two type-II crystals to generate a higher frequency photon (labeled as photon 4). The projection measurements on photon 4 (either at the 45° or at the 135° direction) correspond to the four Bell states of photon 1 and photon 2, $|\Phi_{12}^{(\pm)}\rangle$ and $|\Psi_{12}^{(\pm)}\rangle$.

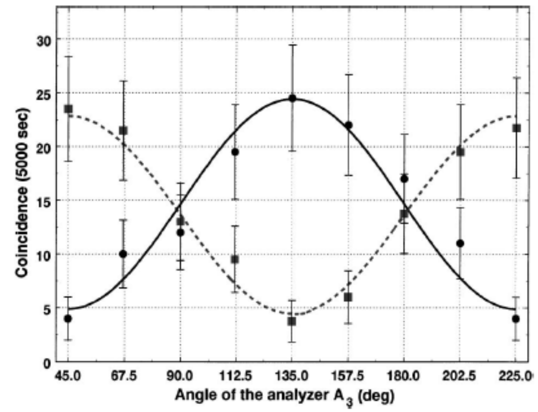
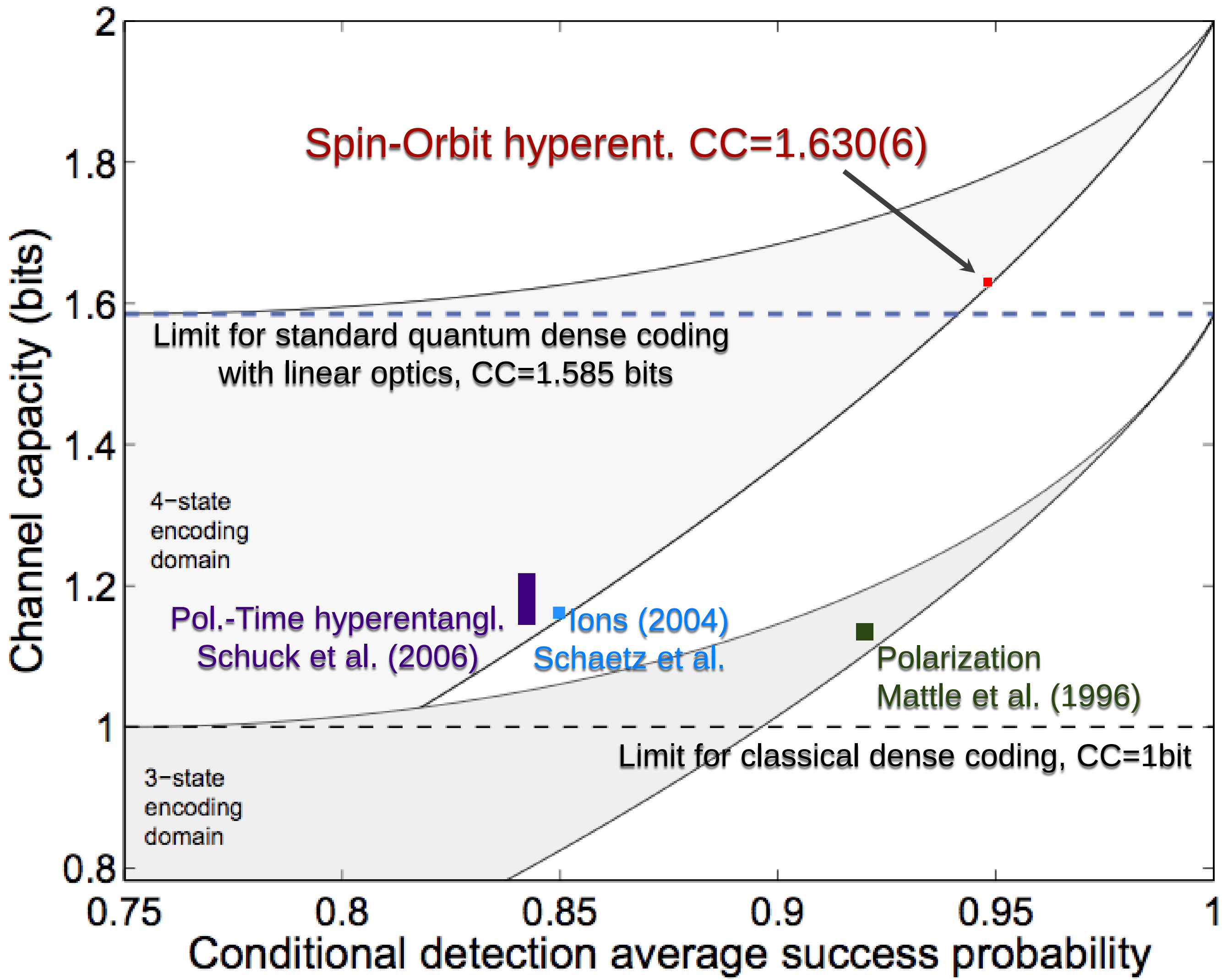


FIG. 2. The solid line (circled data points) is the joint detection rate D_4^{I}-D_3 for 45° linear polarization as an input state. The dashed line (square data points) is for D_4^{II}-D_3 for the same input state. The expected π phase shift is clearly demonstrated.

PROBLEM: The input was a pulse with ??10^9?? photons.

Experimentally reported CC for quantum dense coding

CC = 2.81 bits*



Barreiro et al., Nature Physics 4, 282 (2008)

*Wei et al., PRA **75**, 060305 (2007)

PRL 118, 050501 (2017) PHYSICAL REVIEW LETTERS week ending 3 FEBRUARY 2017

Superdense Coding over Optical Fiber Links with Complete Bell-State Measurements

Brian P. Williams,* Ronald J. Sadlier,† and Travis S. Humble‡
Quantum Computing Institute, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
(Received 2 September 2016; published 1 February 2017)

Adopting quantum communication to modern networking requires transmitting quantum information through a fiber-based infrastructure. We report the first demonstration of superdense coding over optical fiber links, taking advantage of a complete Bell-state measurement enabled by time-polarization hyperentanglement, linear optics, and common single-photon detectors. We demonstrate the highest single-qubit channel capacity to date utilizing linear optics, 1.665 ± 0.018, and we provide a full experimental implementation of a hybrid, quantum-classical communication protocol for image transfer.

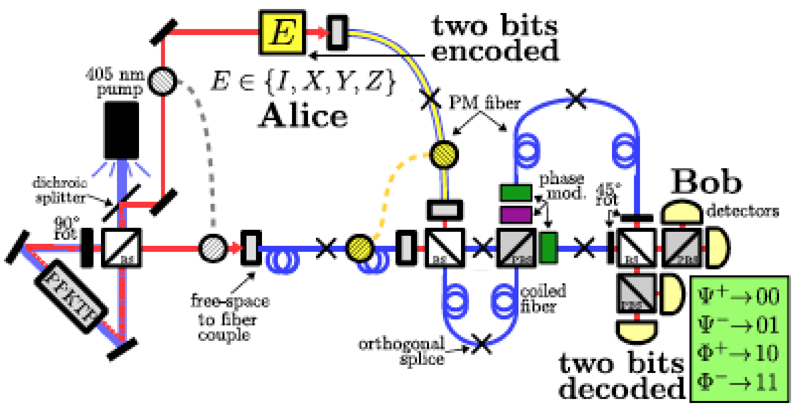


FIG. 3. To implement superdense coding, Alice and Bob initially each receive one photon from a time-polarization hyperentangled photon pair. Alice performs one of four operations on her photon, which encodes two bits on the nonlocal two-photon Bell state. Alice transmits her photon to Bob, who performs a Bell-state measurement, i.e., decodes two bits. bs ≡ beam splitter, pbs ≡ polarizing beam splitter, and PPKTP ≡ potassium titanyl phosphate

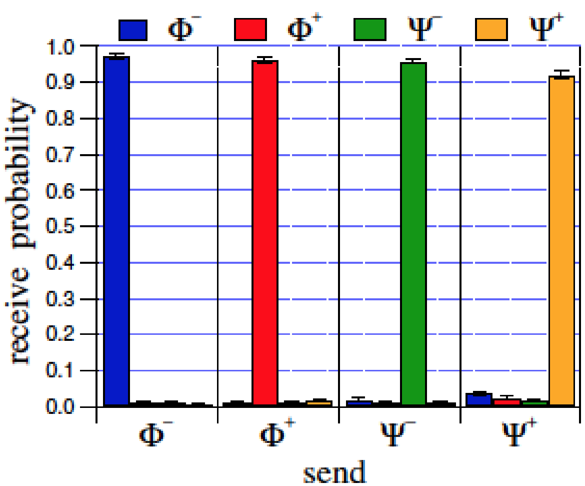


FIG. 4. The conditional probabilities $p(y|x)$ of receiving state y given the sent state x using our apparatus give the highest channel capacity to date, 1.665 ± 0.018, by encoding on a single qubit and decoding using linear optics.

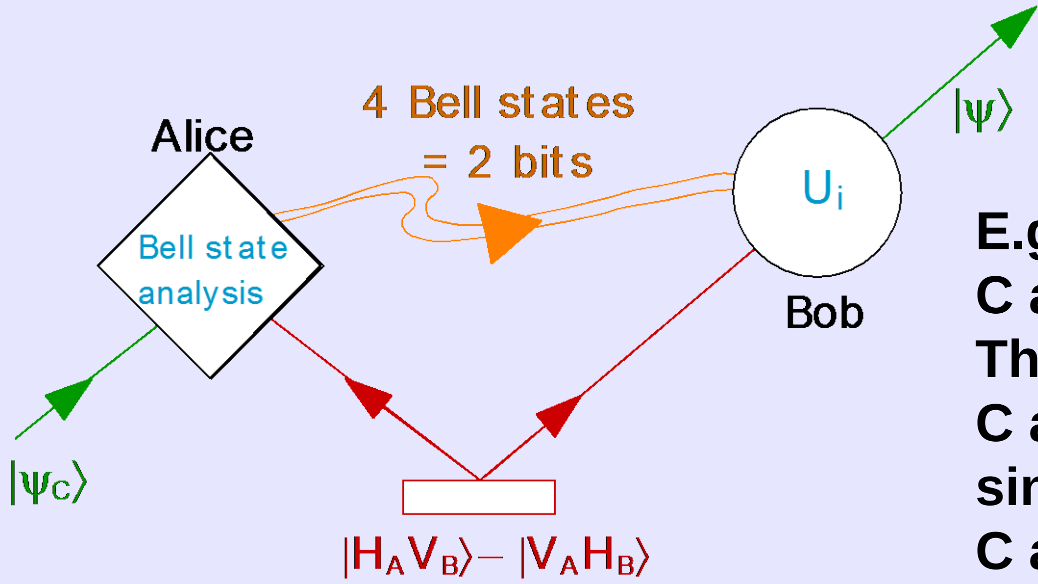
Let’s say we can do ~perfect superdense coding.

Should we?

Quantum Teleportation

The basic idea → transfer the (infinite) amount of information in a qubit from Alice to Bob without sending the qubit itself.

Requires Alice and Bob to share entanglement:



E.g. Alice measures photons C and A to be in a singlet state. Then since C and A are perpendicular, and since A and B are perpendicular, C and A must be *identical*!

Remarks:

- **The original state is gone.**
- **Neither Alice nor Bob know what it was.**
- **Requires classical communication – no superluminal signaling.**
- **Bell state analysis is *hard*.**

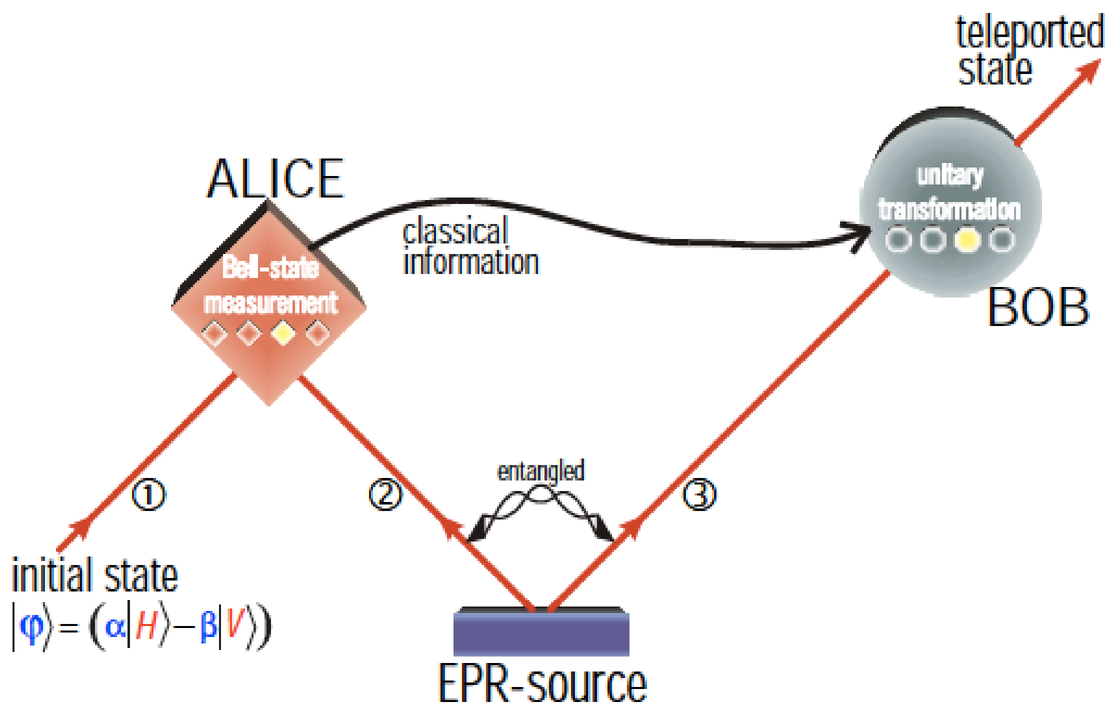
VOLUME 70 29 MARCH 1993 NUMBER 13

Teleporting an Unknown Quantum State via Dual Classical and Einstein-Podolsky-Rosen Channels

PHYSICAL REVIEW LETTERS

Charles H. Bennett,(1) Gilles Brassard,(2) Claude Crépeau,(2),(3) Richard Jozsa,(2) Asher Peres,(4) and William K. Wootters(5)

An unknown quantum state $|\phi\rangle$ can be disassembled into, then later reconstructed from, purely classical information and purely nonclassical Einstein-Podolsky-Rosen (EPR) correlations. To do so the sender, "Alice," and the receiver, "Bob," must prearrange the sharing of an EPR-correlated pair of particles. Alice makes a joint measurement on her EPR particle and the unknown quantum system, and sends Bob the classical result of this measurement. Knowing this, Bob can convert the state of his EPR particle into an exact replica of the unknown state $|\phi\rangle$ which Alice destroyed.



$$\left|\Psi_T\right\rangle\left|\Psi_{AB}\right\rangle =$$

$$= \tfrac{1}{\sqrt{2}}\left(\alpha_0\left|0\right\rangle_T + \alpha_1\left|1\right\rangle_T\right)\otimes\left(\left|0\right\rangle_A\left|1\right\rangle_B - \left|1\right\rangle_A\left|0\right\rangle_B\right)$$

$$= \tfrac{1}{\sqrt{2}}\left(\alpha_0\left|0\right\rangle_T\left|0\right\rangle_A\left|1\right\rangle_B + \alpha_1\left|1\right\rangle_T\left|0\right\rangle_A\left|1\right\rangle_B - \alpha_0\left|0\right\rangle_T\left|1\right\rangle_A\left|0\right\rangle_B - \alpha_1\left|1\right\rangle_T\left|1\right\rangle_A\left|0\right\rangle_B\right)$$

$$= \tfrac{1}{2\sqrt{2}}\left(\alpha_0\left(\Phi^+_{TA} + \Phi^-_{TA}\right)\left|1\right\rangle_B + \alpha_1\left(\Psi^+_{TA} - \Psi^-_{TA}\right)\left|1\right\rangle_B - \alpha_0\left(\Psi^+_{TA} + \Psi^-_{TA}\right)\left|0\right\rangle_B - \alpha_1\left(\Phi^+_{TA} - \Phi^-_{TA}\right)\left|0\right\rangle_B\right)$$

$$\begin{aligned} = \tfrac{1}{2\sqrt{2}}\Big(&\Phi^+_{TA}\left(\alpha_0\left|1\right\rangle_B - \alpha_1\left|0\right\rangle_B\right) \\ &+ \Phi^-_{TA}\left(\alpha_0\left|1\right\rangle_B + \alpha_1\left|0\right\rangle_B\right) \\ &- \Psi^+_{TA}\left(\alpha_0\left|0\right\rangle_B - \alpha_1\left|1\right\rangle_B\right) \\ &- \Psi^-_{TA}\left(\alpha_0\left|0\right\rangle_B + \alpha_1\left|1\right\rangle_B\right)\Big) \end{aligned}$$

Experimental quantum teleportation

NATURE | VOL 390 | 11 DECEMBER 1997

Dik Bouwmeester, Jian-Wei Pan, Klaus Mattle, Manfred Eibl, Harald Weinfurter & Anton Zeilinger

Institut für Experimentalphysik, Universität Innsbruck, Technikerstr. 25, A-6020 Innsbruck, Austria

Quantum teleportation—the transmission and reconstruction over arbitrary distances of the state of a quantum system—is demonstrated experimentally. During teleportation, an initial photon which carries the polarization that is to be transferred and one of a pair of entangled photons are subjected to a measurement such that the second photon of the entangled pair acquires the polarization of the initial photon. This latter photon can be arbitrarily far away from the initial one. Quantum teleportation will be a critical ingredient for quantum computation networks.

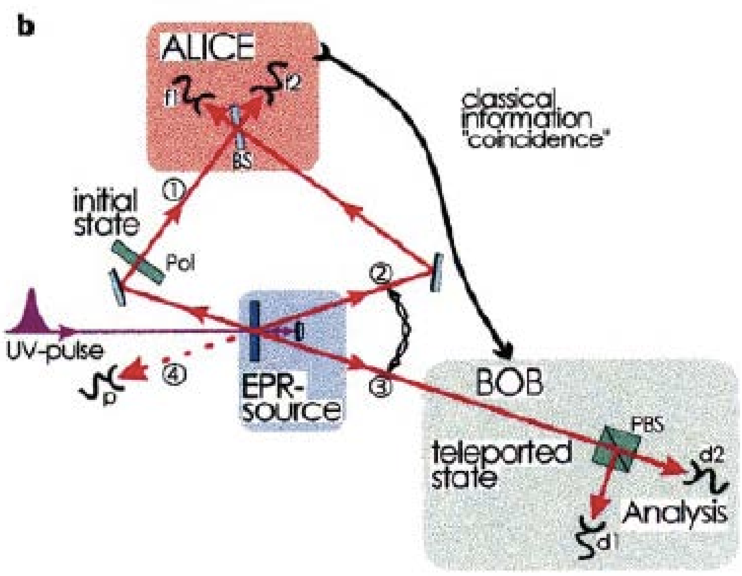


Table 1 Visibility of teleportation in three fold coincidences

Polarization	Visibility
+45°	0.63 ± 0.02
–45°	0.64 ± 0.02
0°	0.66 ± 0.02
90°	0.61 ± 0.02

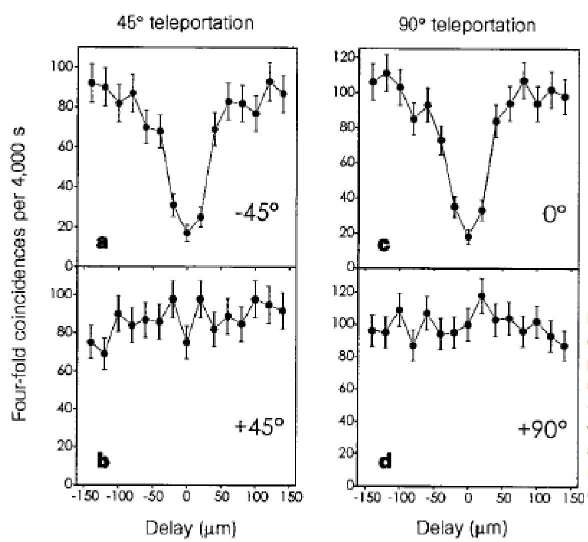
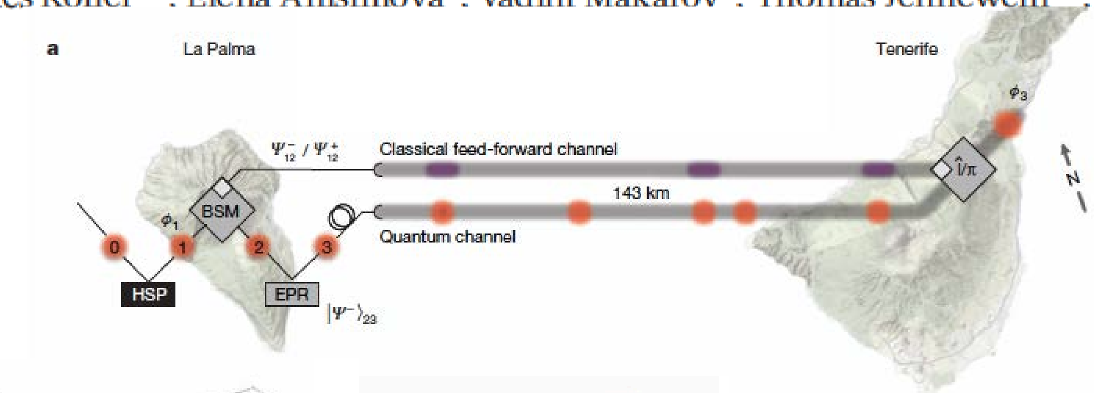


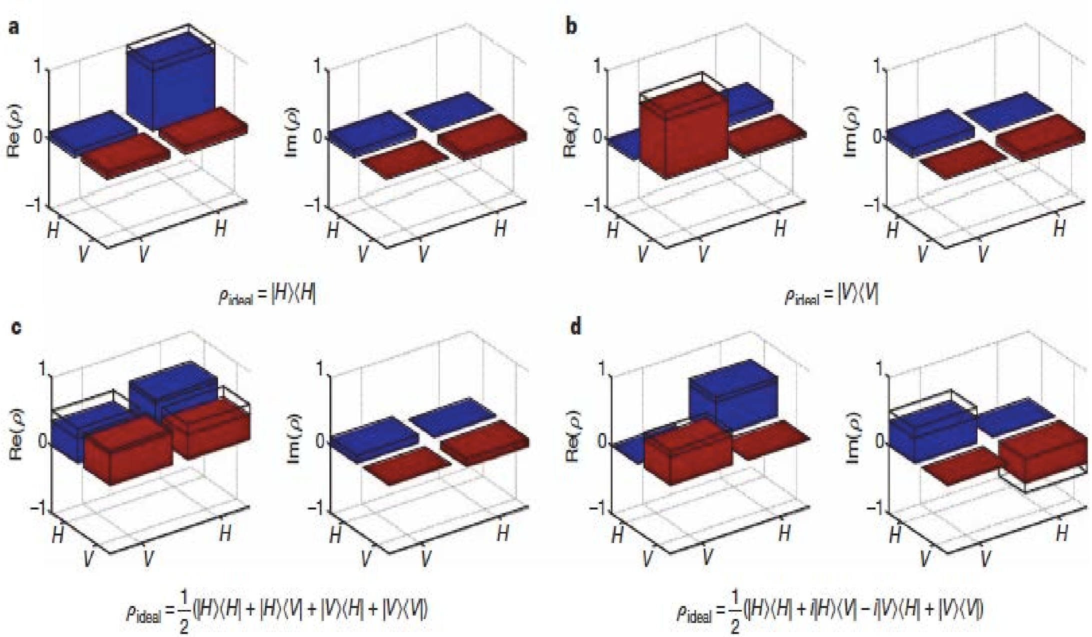
Figure 5 Four-fold coincidence rates (without background subtraction). Conditioning the three-fold coincidences as shown in Fig. 4 on the registration of photon 4 (see Fig. 1b) eliminates the spurious three-fold background. **a** and **b** show the four-fold coincidence measurements for the case of teleportation of the +45° polarization state; **c** and **d** show the results for the +90° polarization state. The visibilities, and thus the polarizations of the teleported photons, obtained without any background subtraction are 70% ± 3%. These results for teleportation of two non-orthogonal states prove that we have demonstrated teleportation of the quantum state of a single photon.

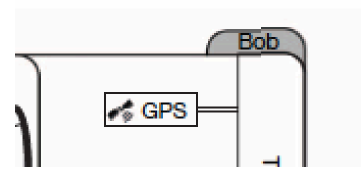
Quantum teleportation over 143 kilometres using active feed-forward

13 SEPTEMBER 2012 | VOL 489 | NATURE | 269

Xiao-Song Ma[1,2]†, Thomas Herbst[1,2], Thomas Scheidl[1], Daqing Wang[1], Sebastian Kropatschek[1], William Naylor[1], Bernhard Wittmann[1,2], Alexandra Mech[1,2], Johannes Kofler[1,3], Elena Anisimova[4], Vadim Makarov[4], Thomas Jennewein[1,4], Rupert Ursin[1] & Anton Zeilinger[1,2]







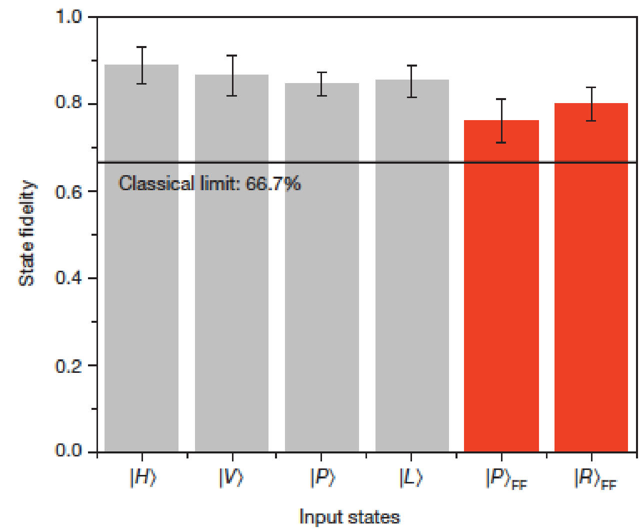


Figure 2 | State tomography results of the four quantum states without feed-forward over the 143-km free-space channel with the BSM outcome of $|\Psi^-\rangle_{12}$. The bar graphs show the reconstructed density matrices ρ for the four

Quantum teleportation and entanglement distribution over 100-kilometre free-space channels

Juan Yin[1]*, Ji-Gang Ren[1]*, He Lu[1]*, Yuan Cao[1], Hai-Lin Yong[1], Yu-Ping Wu[1], Chang Liu[1], Sheng-Kai Liao[1], Fei Zhou[1], Yan Jiang[1], Xin-Dong Cai[1], Ping Xu[1], Ge-Sheng Pan[1], Jian-Jun Jia[2], Yong-Mei Huang[3], Hao Yin[1], Jian-Yu Wang[2], Yu-Ao Chen[1], Cheng-Zhi Peng[1] & Jian-Wei Pan[1]

9 AUGUST 2012 | VOL 488 | NATURE | 185

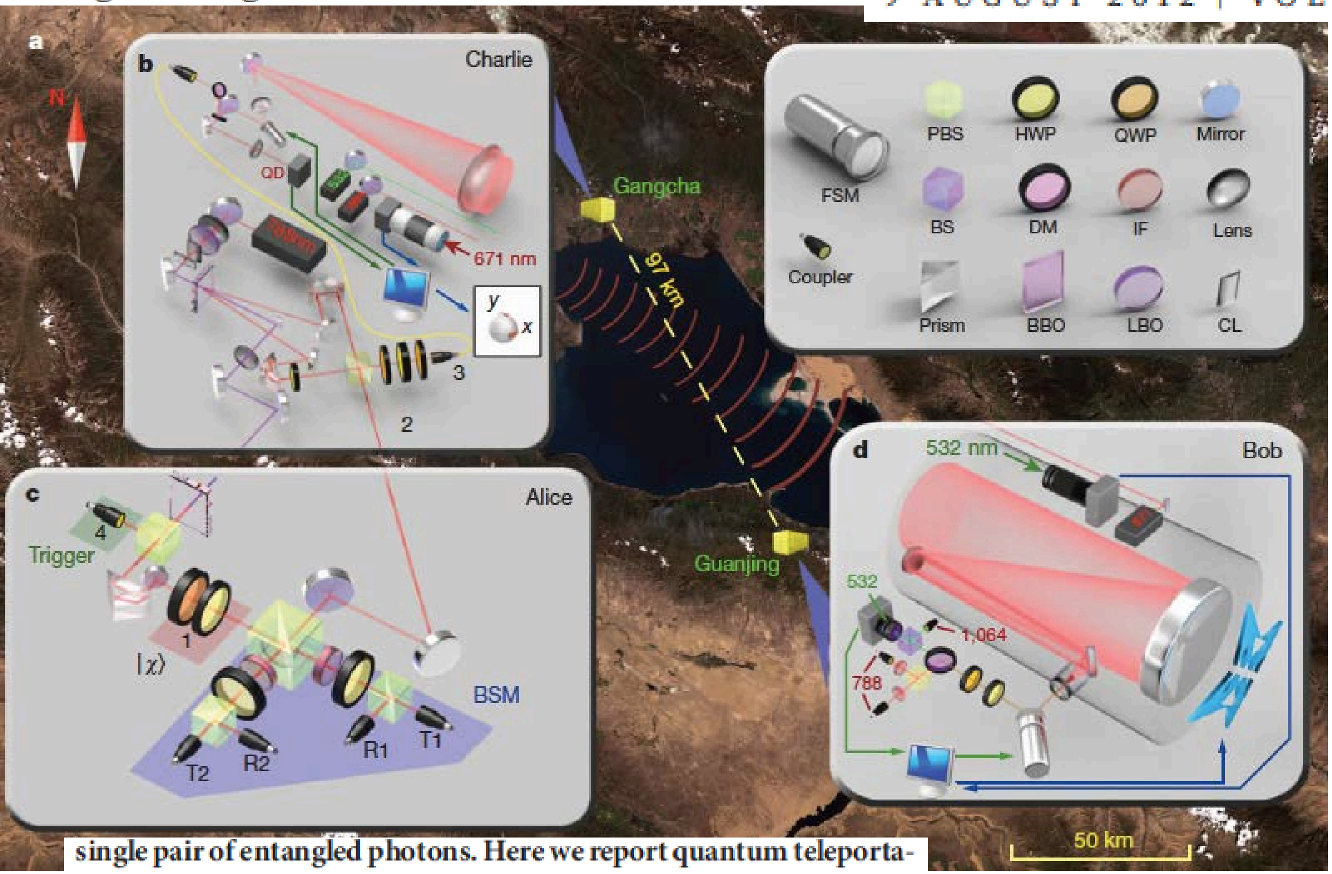


Table 1 | Fidelity of quantum teleportation over 97 km

State	Fidelity
H	0.814 ± 0.031
V	0.886 ± 0.024
+	0.773 ± 0.031
−	0.781 ± 0.031
R	0.808 ± 0.026
L	0.760 ± 0.027

The data were accumulated for 14,400s. Errors shown are statistical errors, ±1 s.d.

single pair of entangled photons. Here we report quantum teleportation of independent qubits over a 97-kilometre one-link free-space channel with multi-photon entanglement. An average fidelity of 80.4 ± 0.9 per cent is achieved for six distinct states. Furthermore, we demonstrate entanglement distribution over a two-link channel, in which the entangled photons are separated by 101.8 kilometres. Violation of the Clauser–Horne–Shimony–Holt inequality[4] is observed without the locality loophole. Besides being of fundamental

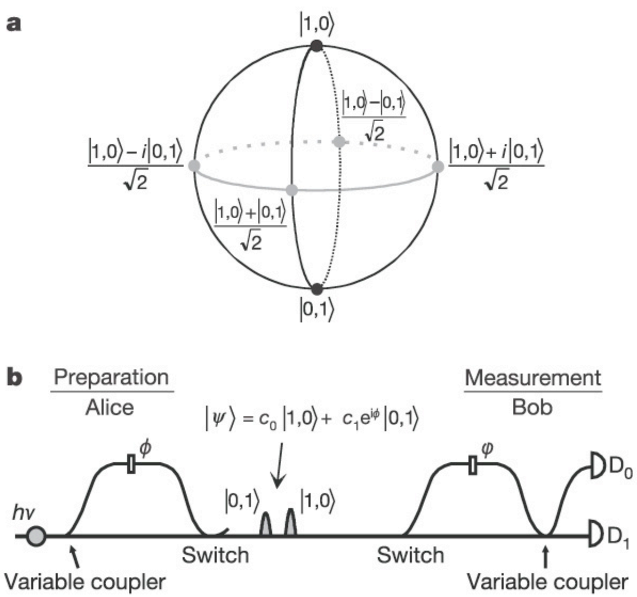
EOMs were controlled by two independent quantum random number generators, each of which generates a random number every 20 μs (less than 340 μs). Thus the measurement-setting choices are also space-like separated. Hence, the locality loophole is closed.

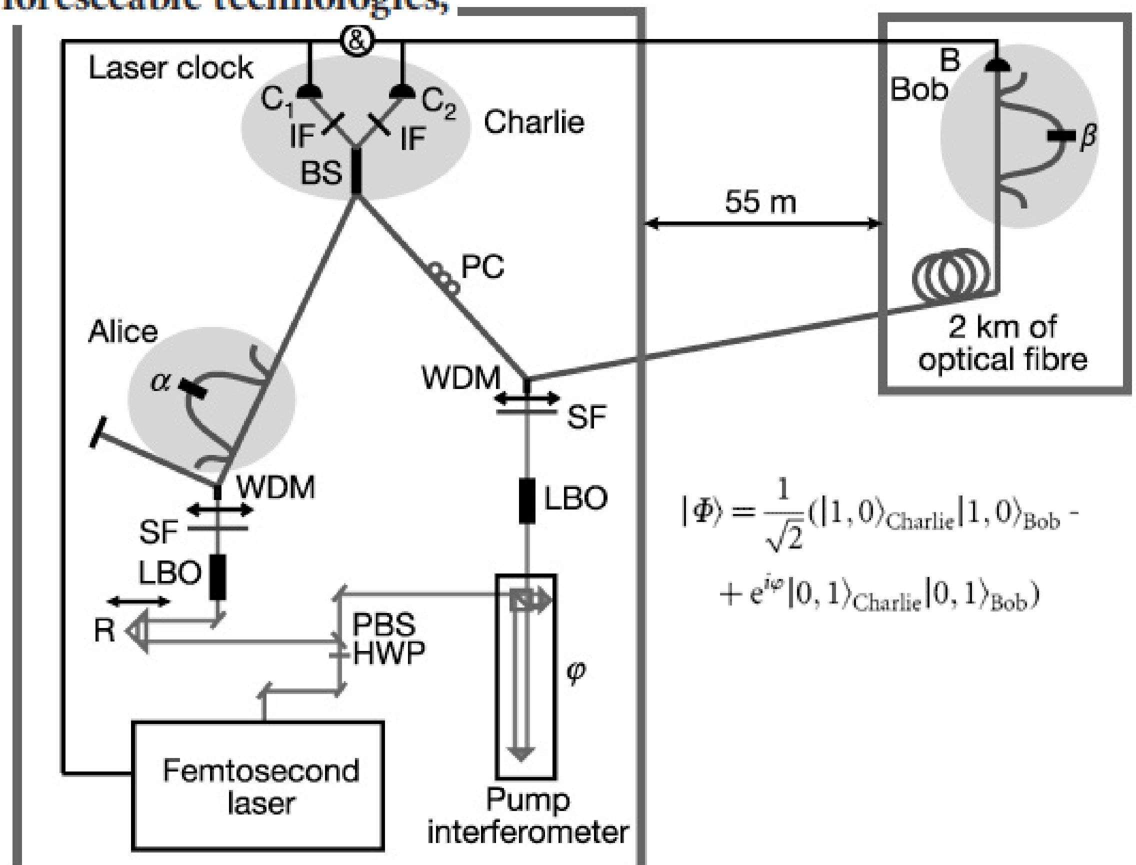
Long-distance teleportation of qubits at telecommunication wavelengths

NATURE | VOL 421 | 30 JANUARY 2003

I. Marcikic*†, H. de Riedmatten*†, W. Tittel*‡, H. Zbinden* & N. Gisin*

short distances. Here we report a long-distance experimental demonstration of probabilistic quantum teleportation. Qubits carried by photons of 1.3 µm wavelength are teleported onto photons of 1.55 µm wavelength from one laboratory to another, separated by 55 m but connected by 2 km of standard telecommunications fibre. The first (and, with foreseeable technologies,





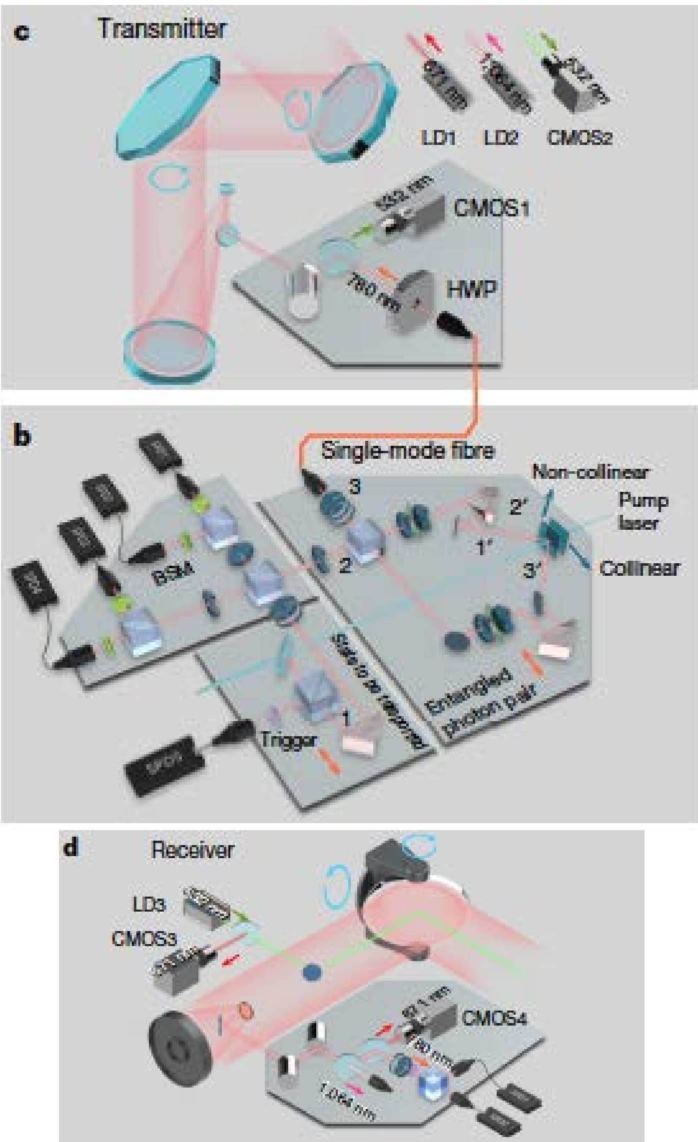
$$|\Phi\rangle = \frac{1}{\sqrt{2}}(|1,0\rangle_{\mathrm{Charlie}}|1,0\rangle_{\mathrm{Bob}} - + e^{i\varphi}|0,1\rangle_{\mathrm{Charlie}}|0,1\rangle_{\mathrm{Bob}})$$

fidelity = 85 ± 2.5%

LETTER

doi:10.1038/nature23675

Ground-to-satellite quantum teleportation



Zhang[2,3], Sheng-Kai Liao[1,2], Juan Yin[1,2], Wei-Yue Liu[1,2], Wen-Qi Cai[1,2],
n[1,2], Yong-Qiang Yao[4], Ji Li[5], Hai-Yan Wu[5], Song Wan[6], Lei Liu[6],
Peng Shang[1,2], Cheng Guo[1,2], Ru-Hua Zheng[7], Kai Tian[8], Zhen-Cai Zhu[6],
Ao Chen[1,2], Cheng-Zhi Peng[1,2], Jian-Yu Wang[2,3] & Jian-Wei Pan[1,2]

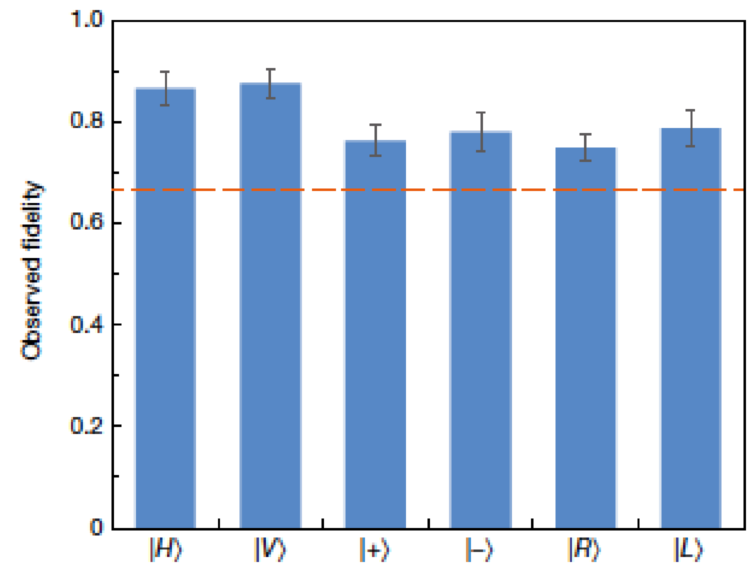


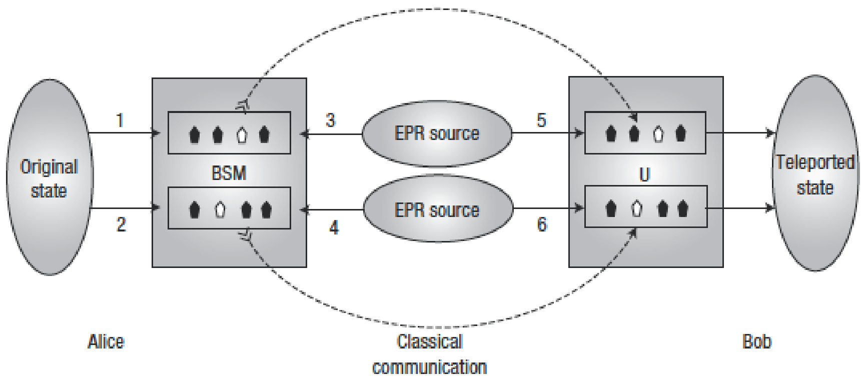
Figure 3 | Fidelity of the teleportation state for the six quantum states, with data taken for 32 orbits. Details of the date, the highest altitude angles and the ground-to-satellite distance for the 32 orbits are provided in Extended Data Table 1. All of the fidelities are well above the classical limit of 2/3 (dashed line). The error bars represent one standard deviation, calculated from Poissonian counting statistics of the raw detection events.

The main sources of fidelity error are double-pair emission of SPDC (6%), partial photon distinguishability (10%), uplink polarization distortion (3%) and background dark count (4%);

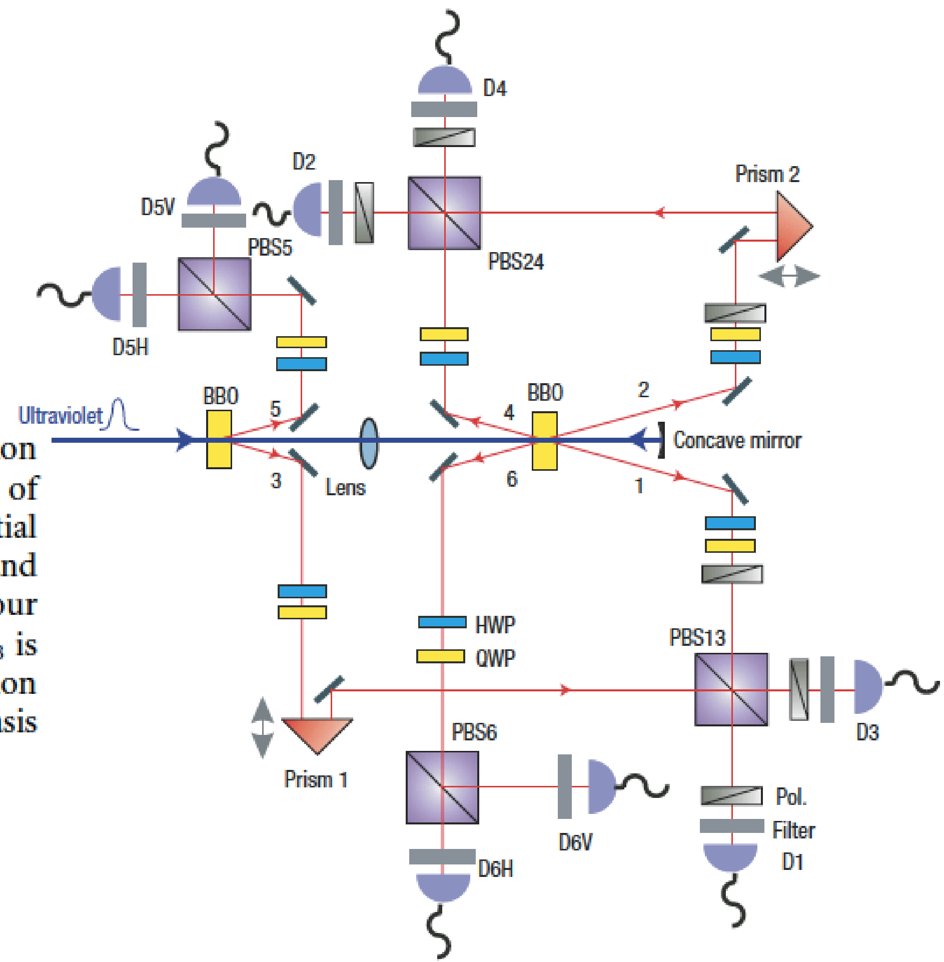
Experimental quantum teleportation of a two-qubit composite system

Published online: 17 September 2006; doi:10.1038/nphys417

QIANG ZHANG[1,2]*, ALEXANDER GOEBEL[1], CLAUDIA WAGENKNECHT[1], YU-AO CHEN[1], BO ZHAO[1], TAO YANG[2], ALOIS MAIR[1], JÖRG SCHMIEDMAYER[1,3] AND JIAN-WEI PAN[1,2]*



1 and 2. To demonstrate that our two-qubit teleportation protocol works for a general unknown polarization state of photons 1 and 2, we decide to teleport three different initial states: $|\chi\rangle_A = |H\rangle|V\rangle$, $|\chi\rangle_B = (|H\rangle + |V\rangle)(|H\rangle - i|V\rangle)/\sqrt{2}$ and $|\chi\rangle_C = (|H\rangle|V\rangle - |V\rangle|H\rangle)/\sqrt{2}$. $|\chi\rangle_A$ is simply one of the four computational basis vectors in the two-qubit Bloch sphere; $|\chi\rangle_B$ is composed of a linear polarization state and a circular polarization state, which is also a superposition of all four computational basis vectors; and $|\chi\rangle_C$ is a maximally entangled state.



Experimental quantum teleportation of a two-qubit composite system

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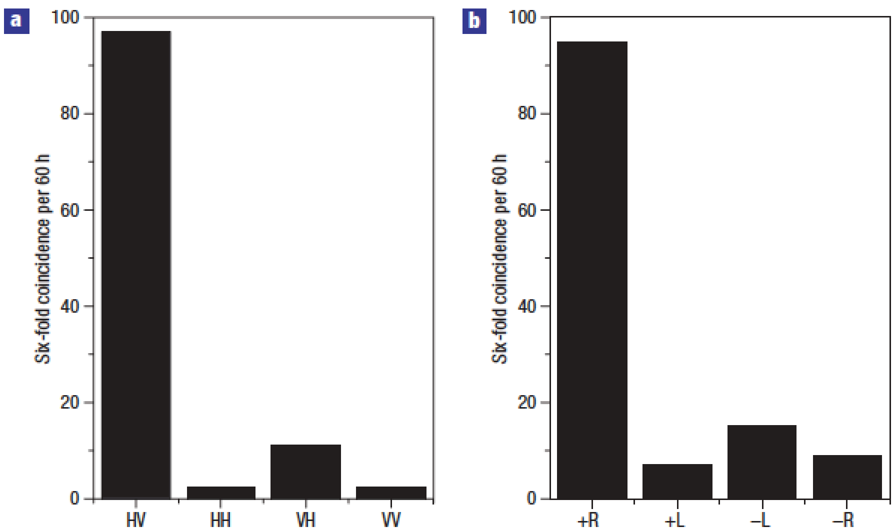


PBSs. On the basis of our original data, we conclude that the fidelity for $|\chi\rangle_A$ or $|\chi\rangle_B$ is 0.86 ± 0.03 or 0.75 ± 0.02, respectively.

$0.65\pm0.03.$

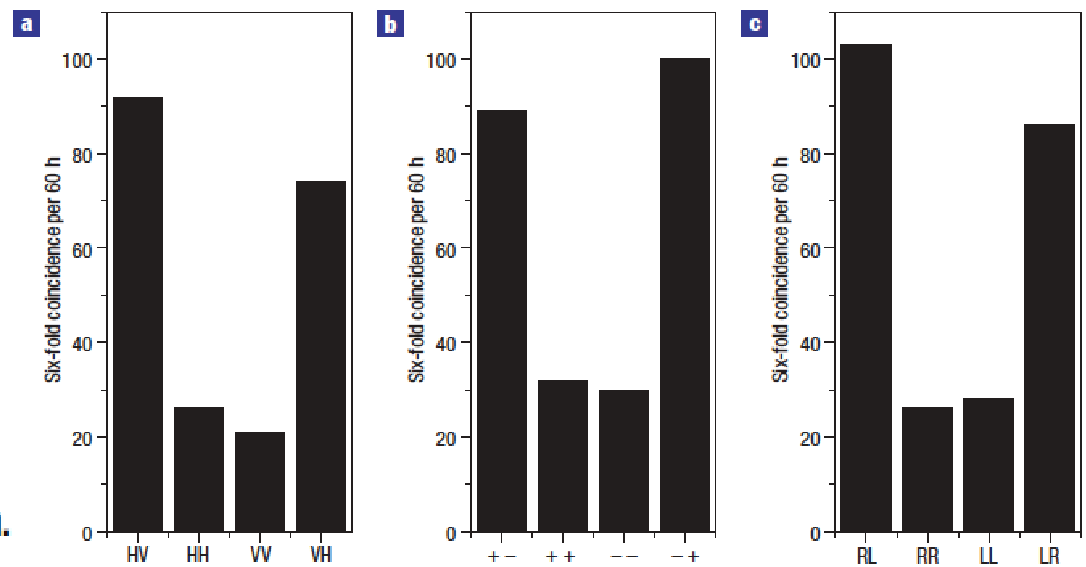
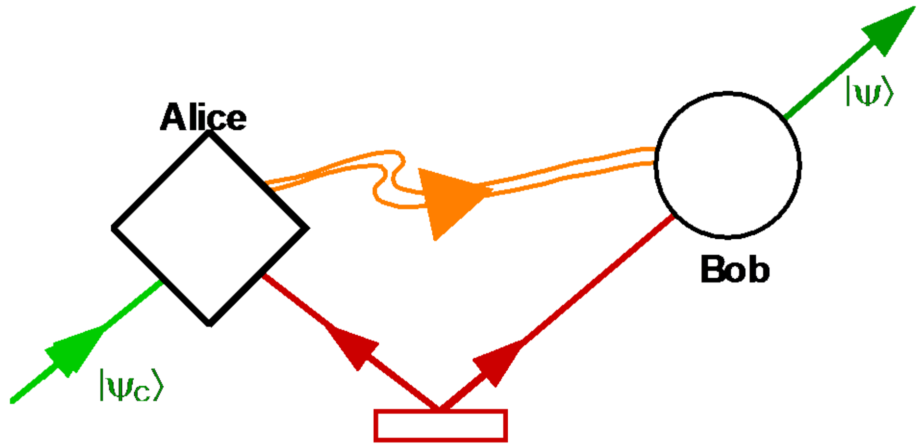


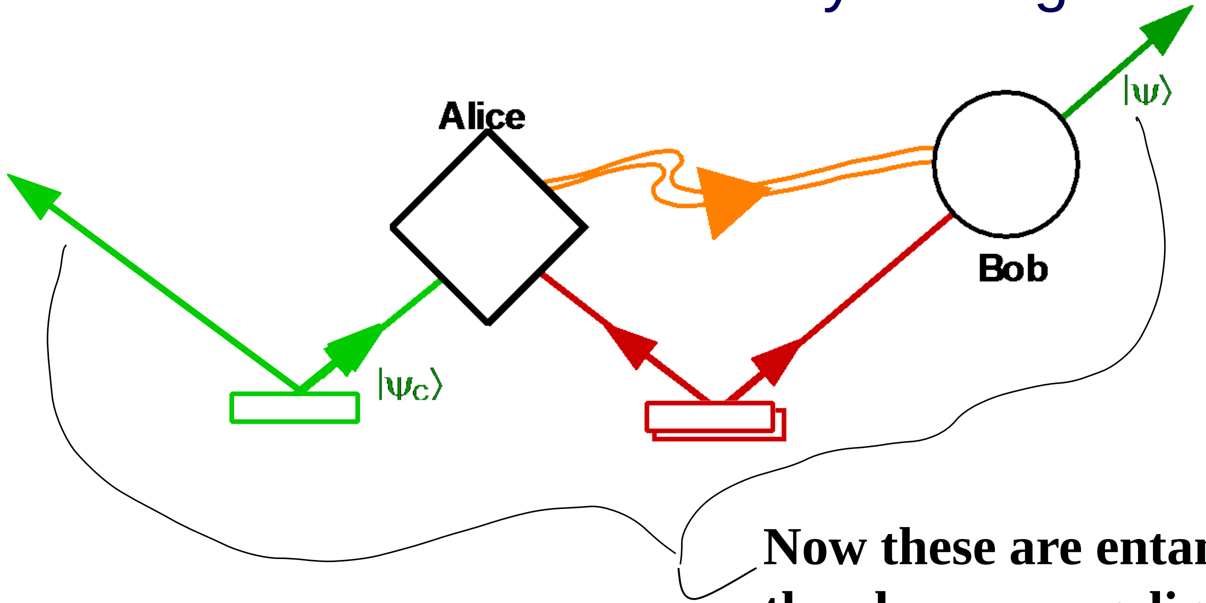
Figure 4 Experimental results for $|\chi\rangle_C$ teleportation.

Teleportation



Entanglement Swapping

What if the unknown state is already entangled to a 4th particle?



Now these are entangled, despite that they have never directly interacted!

PHYSICAL REVIEW LETTERS

VOLUME 80 4 MAY 1998 NUMBER 18

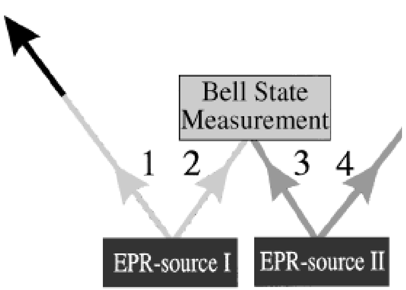
Experimental Entanglement Swapping: Entangling Photons That Never Interacted

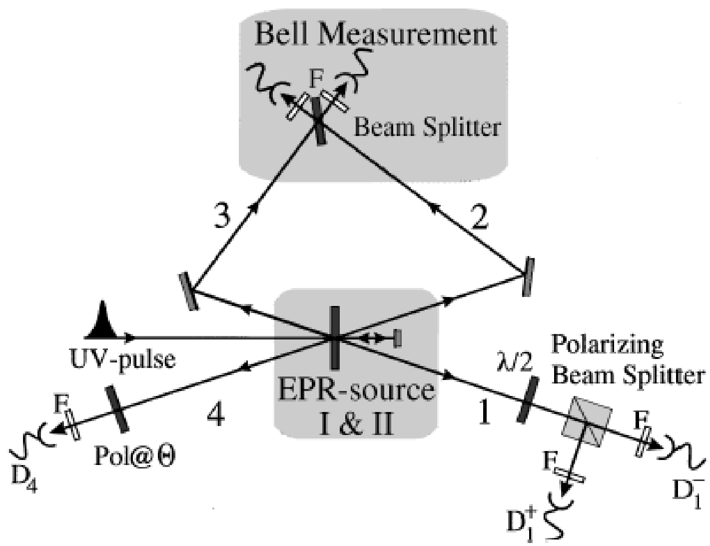
Jian-Wei Pan, Dik Bouwmeester, Harald Weinfurter, and Anton Zeilinger

Institut für Experimentalphysik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria

(Received 6 February 1998)

We experimentally entangle freely propagating particles that never physically interacted with one another or which have never been dynamically coupled by any other means. This demonstrates that quantum entanglement requires the entangled particles neither to come from a common source nor to have interacted in the past. In our experiment we take two pairs of polarization entangled photons and subject one photon from each pair to a Bell-state measurement. This results in projecting the other two outgoing photons into an entangled state. [S0031-9007(98)05913-4





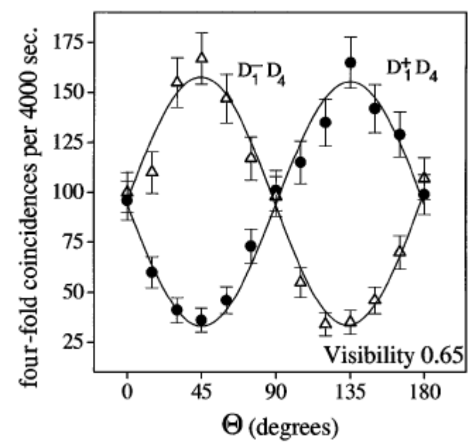
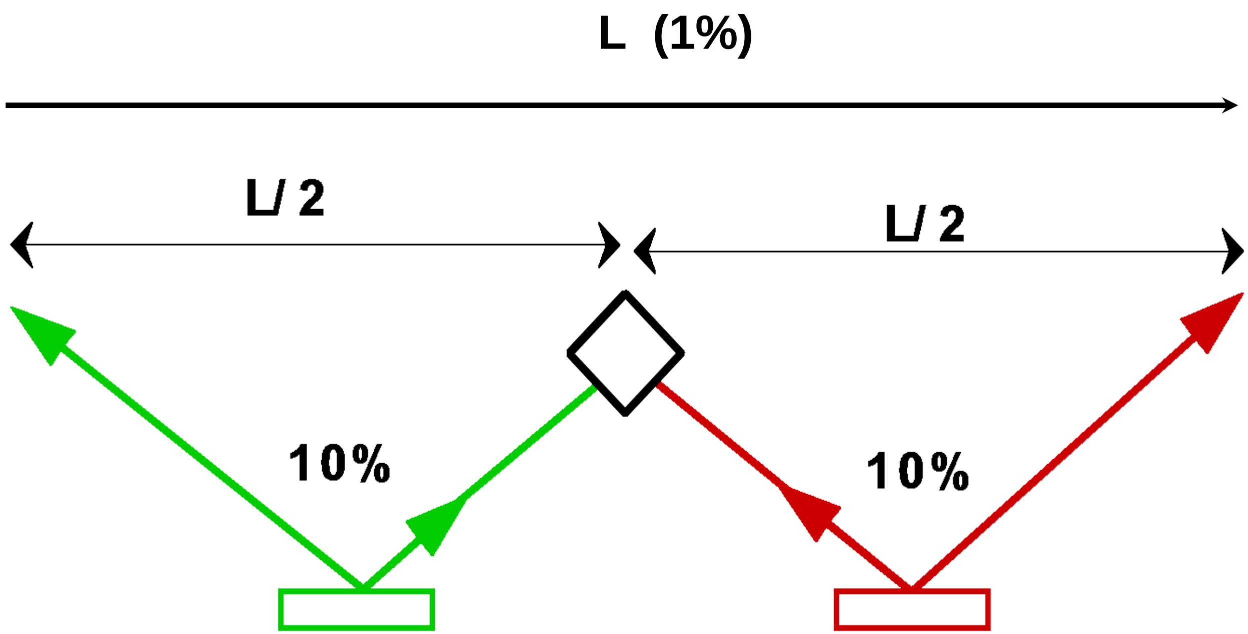


FIG. 3. Entanglement verification. Fourfold coincidences, resulting from twofold coincidence $D1^+D4$ and $D1^-D4$ conditioned on the twofold coincidences of the Bell-state measurement, when varying the polarizer angle Θ. The two complementary sine curves with a visibility of 0.65 ± 0.02 demonstrate that photons 1 and 4 are polarization entangled.

V = 65% (> 50%, <71%)

Entanglement Swapping

Might enable q. cryptography over longer distances (q. repeaters):



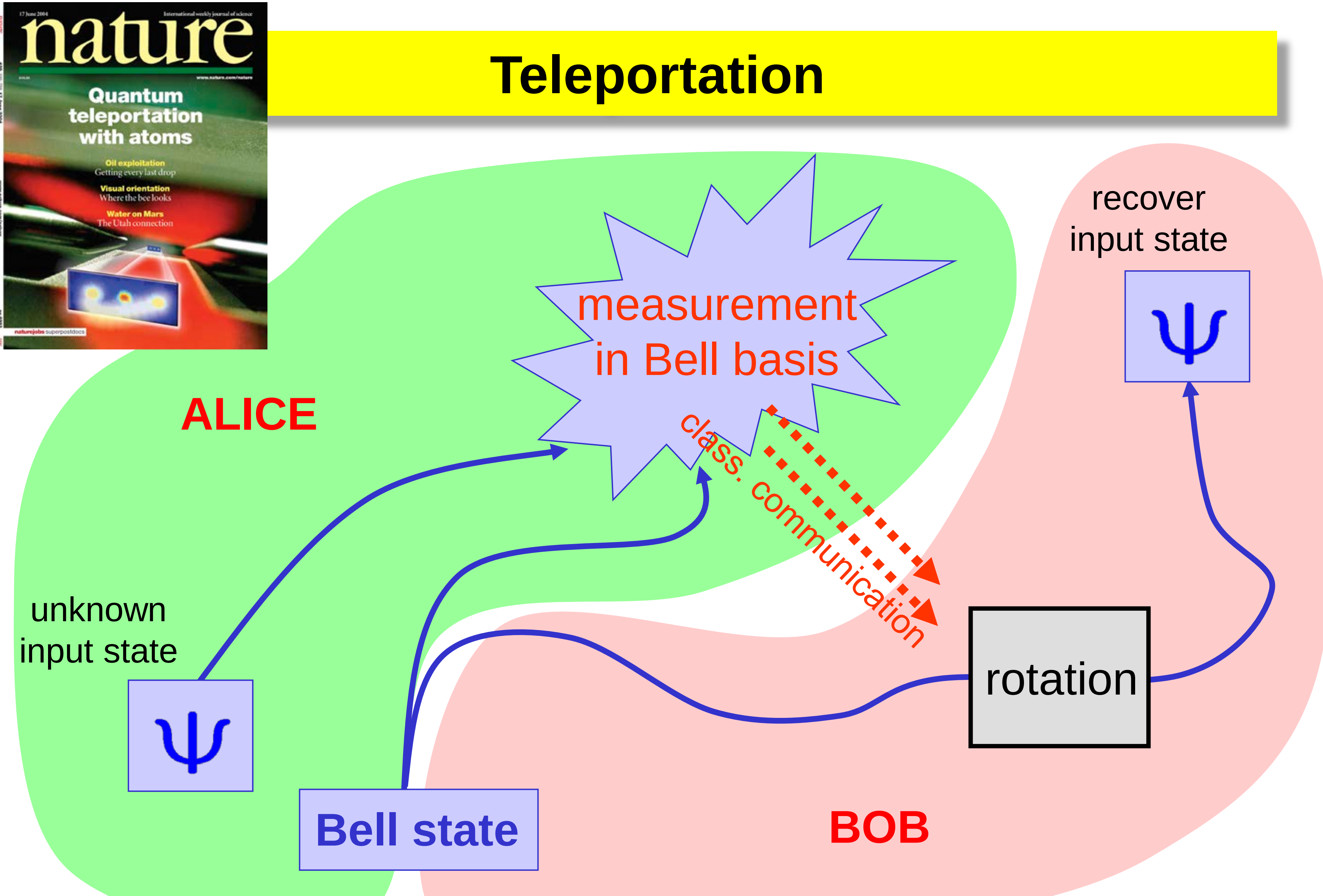
Need ~100 pairs

Need ~20 pairs (if they can be successfully transmitted *independently!*)

Requirements:

- **quantum memory, so we can wait until we have a pair from both sides**
- **a *heralded* quantum memory**

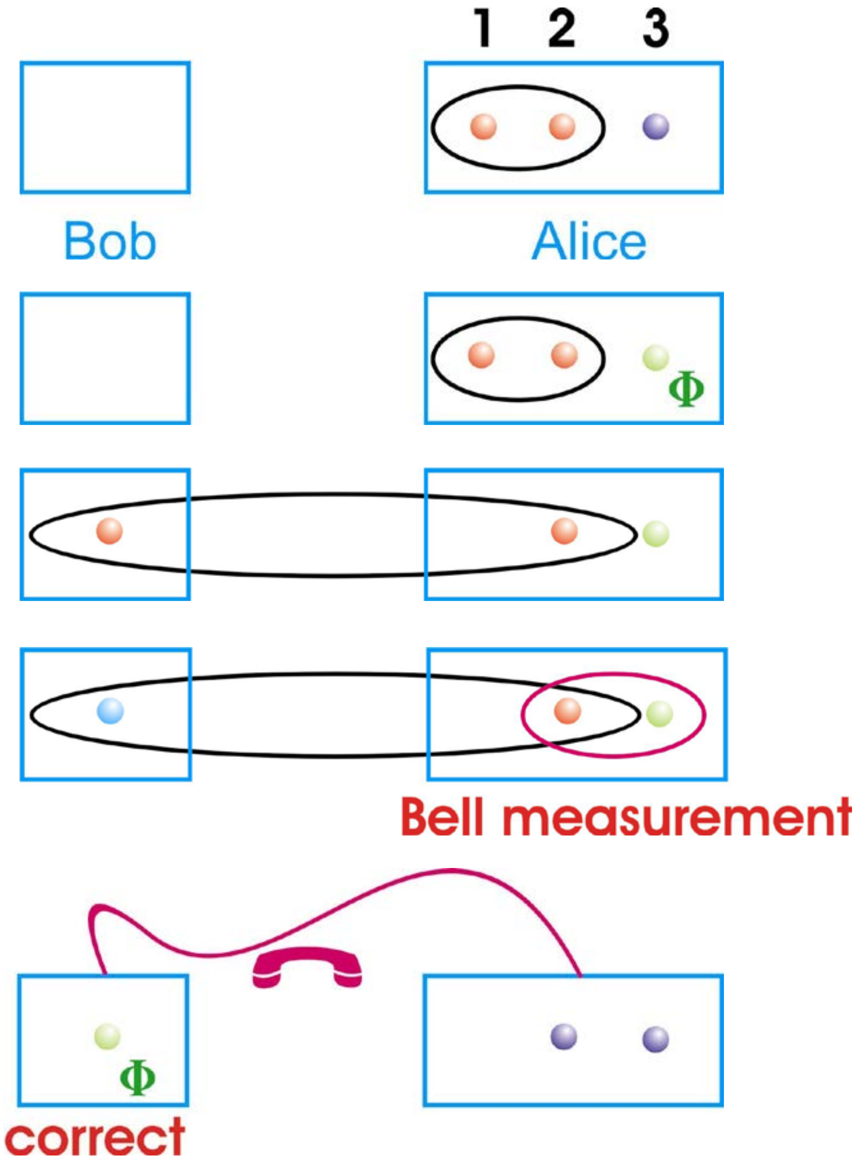
Teleportation



M. Riebe et al., Nature **429**, 734 (2004)

M.D. Barrett et al., Nature **429**, 737 (2004)

Teleportation protocol



i) Create entangled pair between qubit 1 and 2).

ii) Prepare qubit 3 in arbitrary state √.

iii) Move qubit 1 to remote location.

iv) Do Bell-measurement on qubits 2 and 3, measurement outcomes will collapse qubit 1 into one of four possible states.

v) Correct qubit 1 according to the measurement outcome, qubit 1 is now in √.

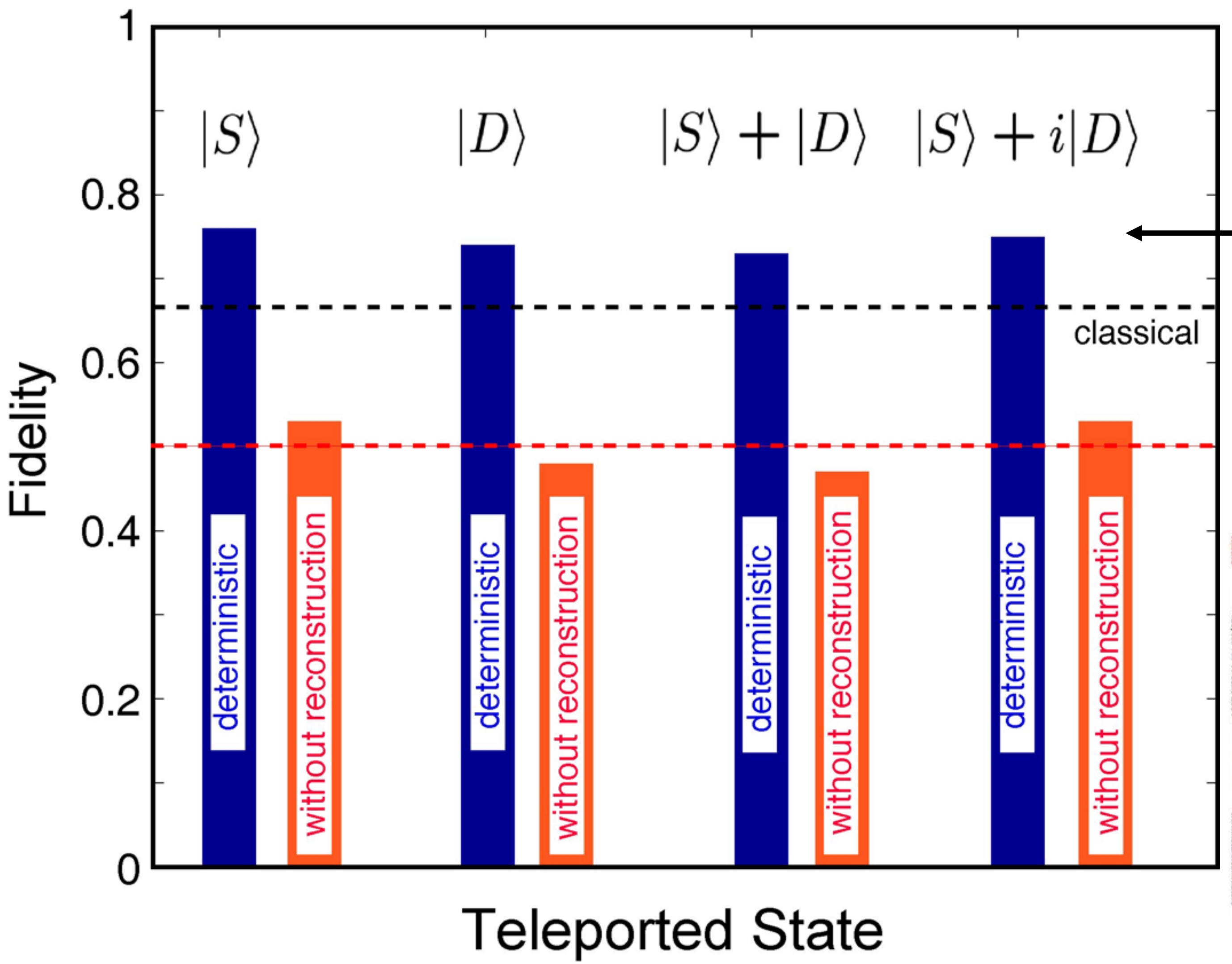
Teleportation experiment

M. D. Barrett et al., *Nature* **429**, 737 (2004)
(also UIBK: M. Riebe et al., ibid.)

Average fidelity 78% > 2/3

rota (correct and measure state

Quantum teleportation with atoms: result

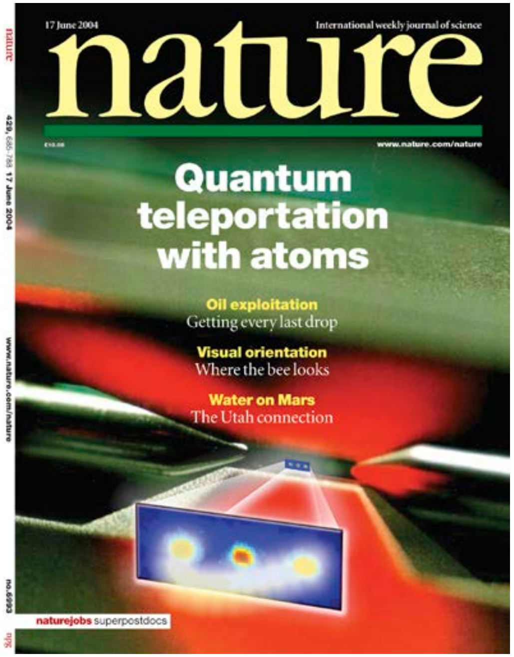


75 %

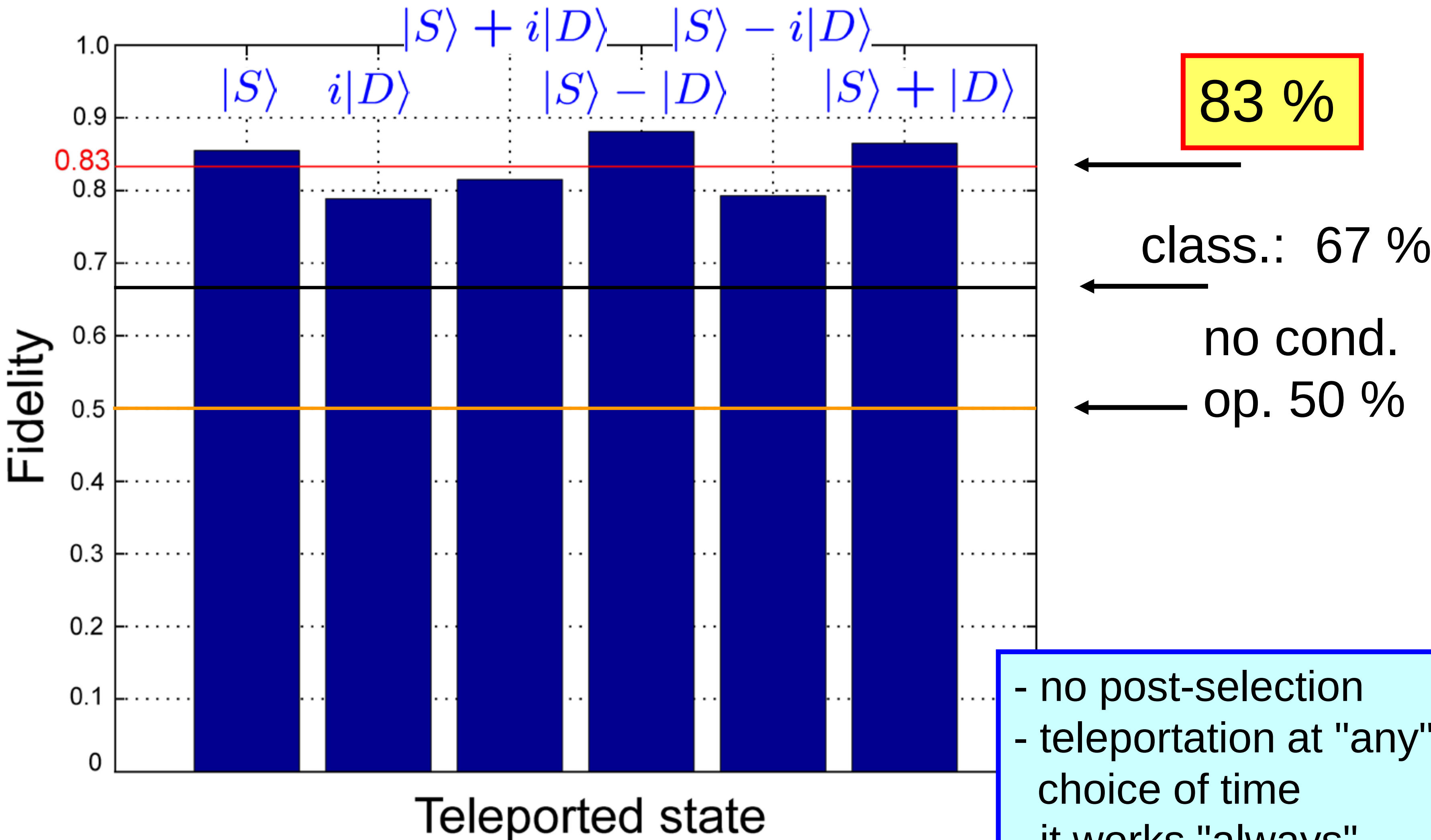
67 %

50 %

M. Riebe et al., Nature **429**, 734 (2004)
similar results by NIST Boulder, ibid., 737 (2004)



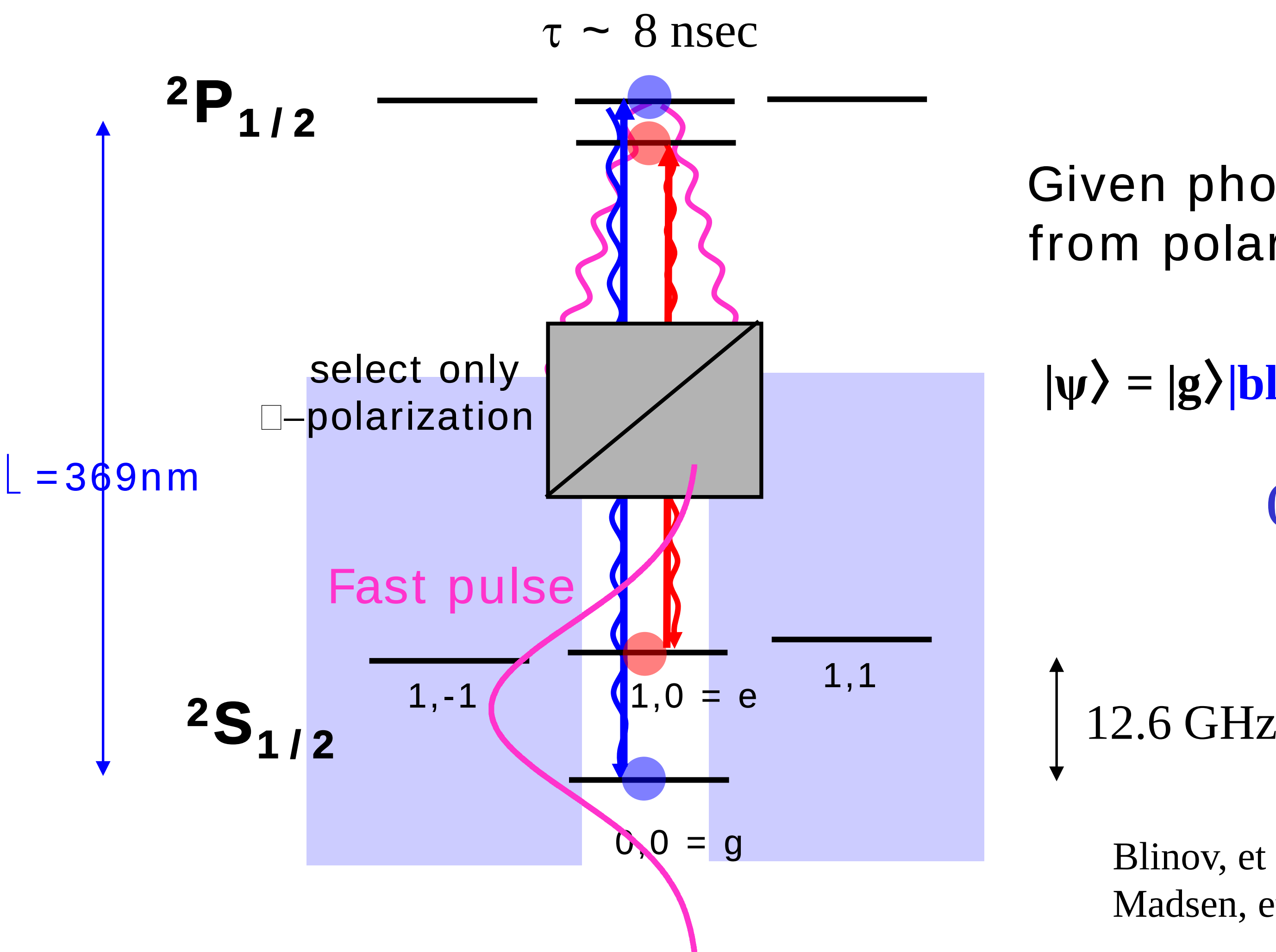
Quantum teleportation with atoms: result



- no post-selection
- teleportation at "any" choice of time
- it works "always"
- only 10 ∫m

Linking atoms with ~~phonons~~ photons

$^{171}Yb^+$

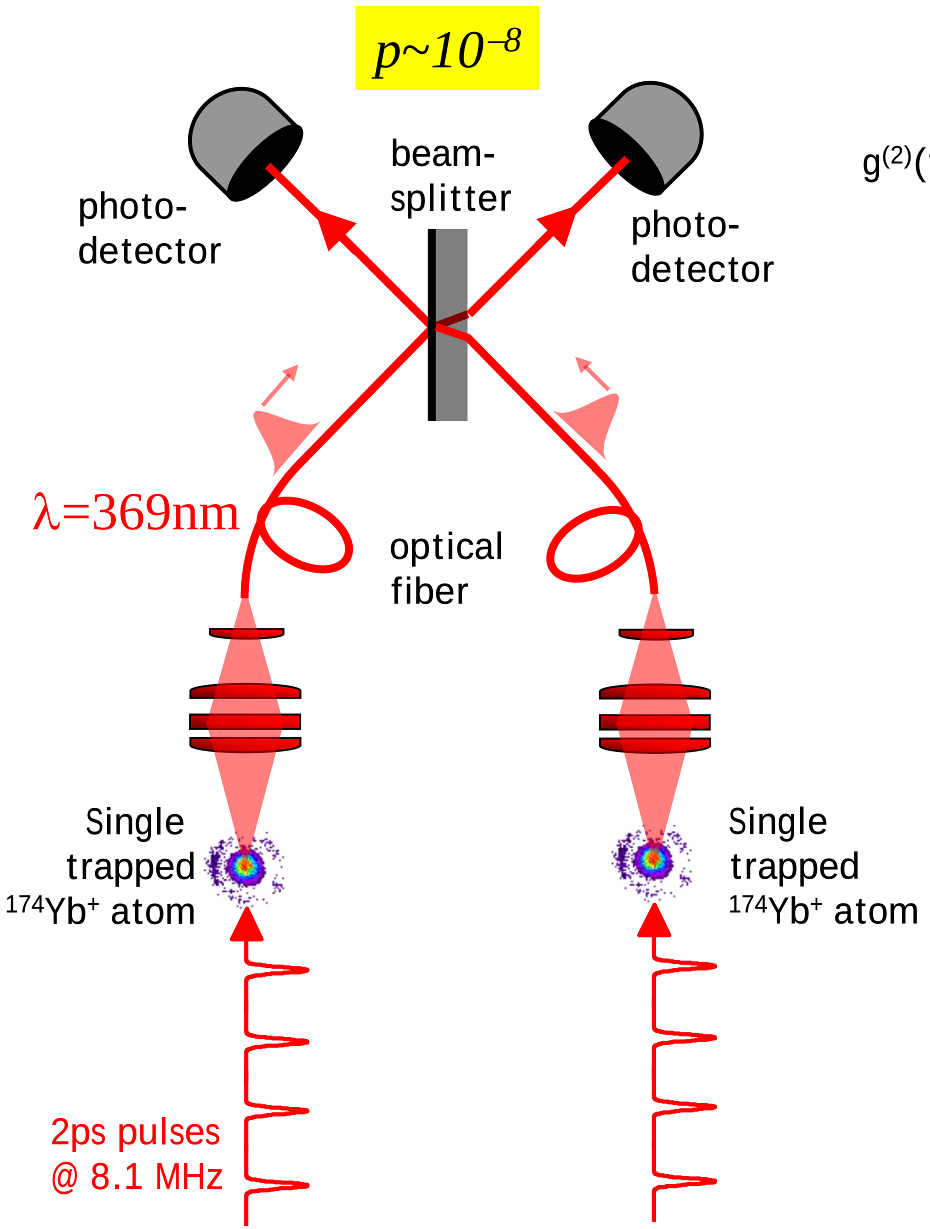


Given photon emerges from polarizer

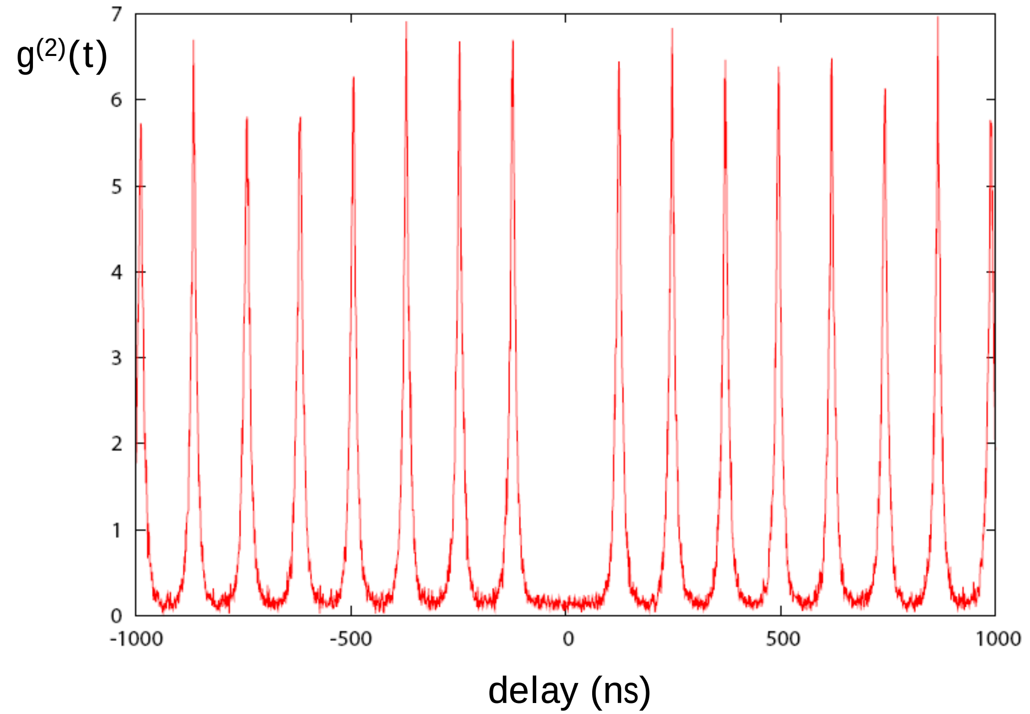
$|\psi\rangle = |g\rangle|\text{blue}\rangle + |e\rangle|\text{red}\rangle$

(post-selected)

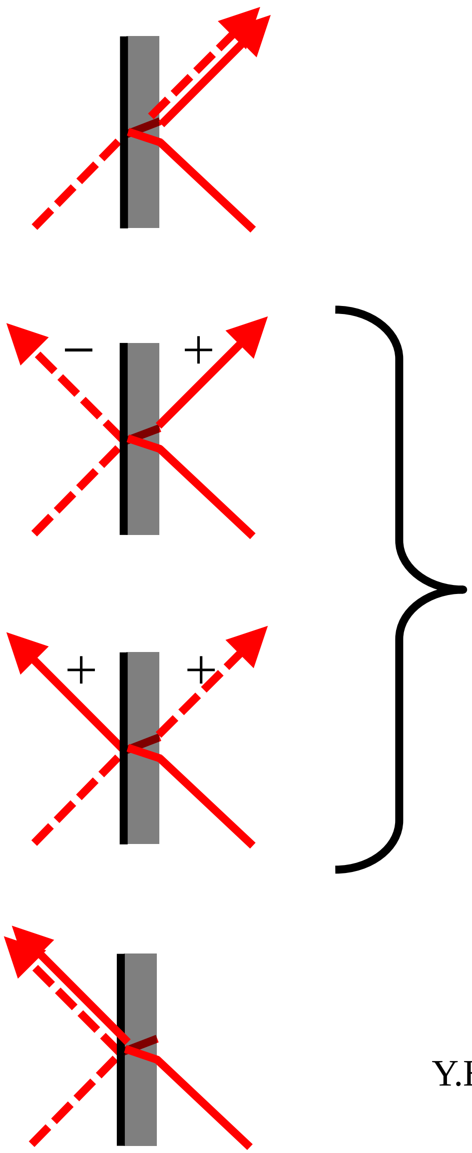
Blinov, et al., Nature **428**, 153 (2004)
Madsen, et al., PRL **97** 040505 (2006)



excellent single-photon source

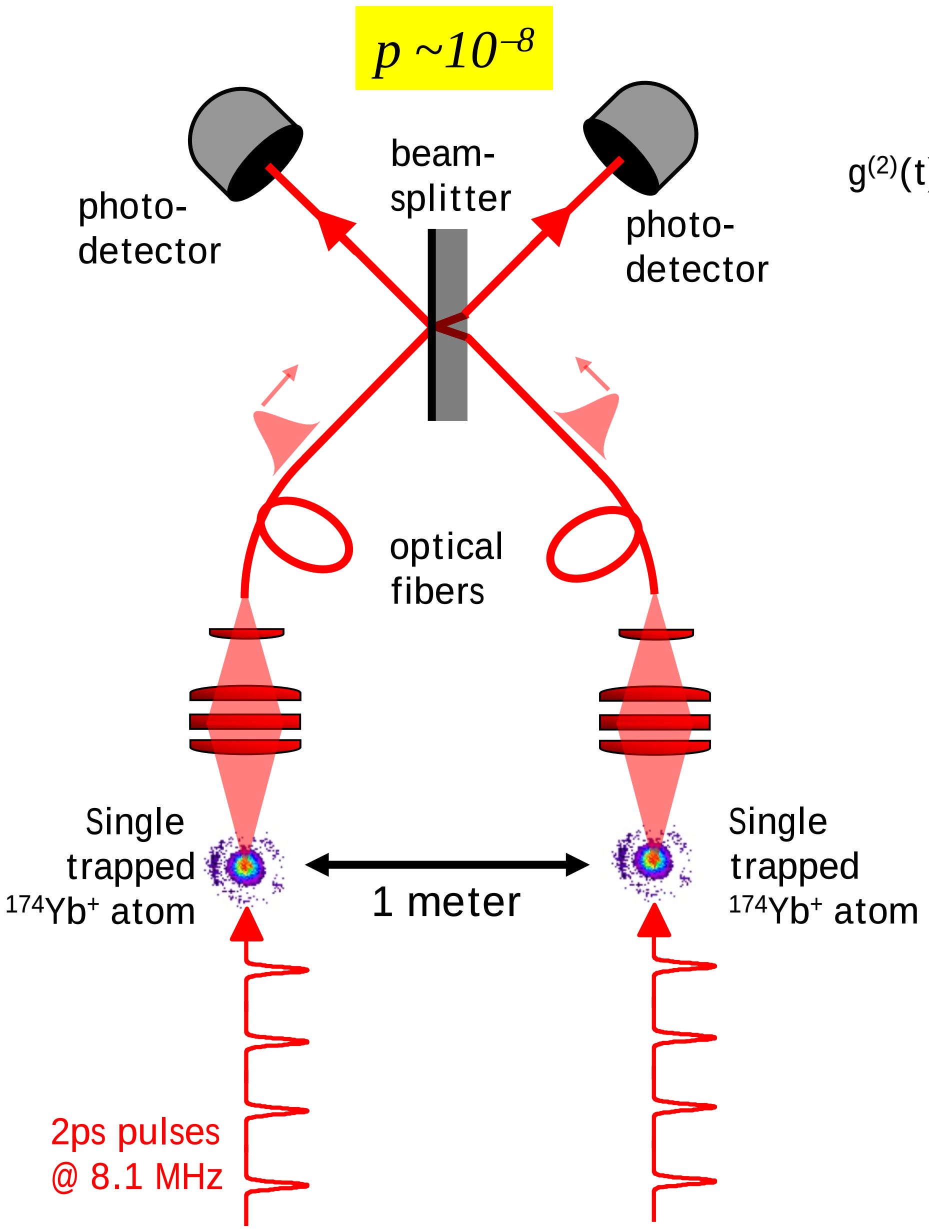


Two-photon Interference

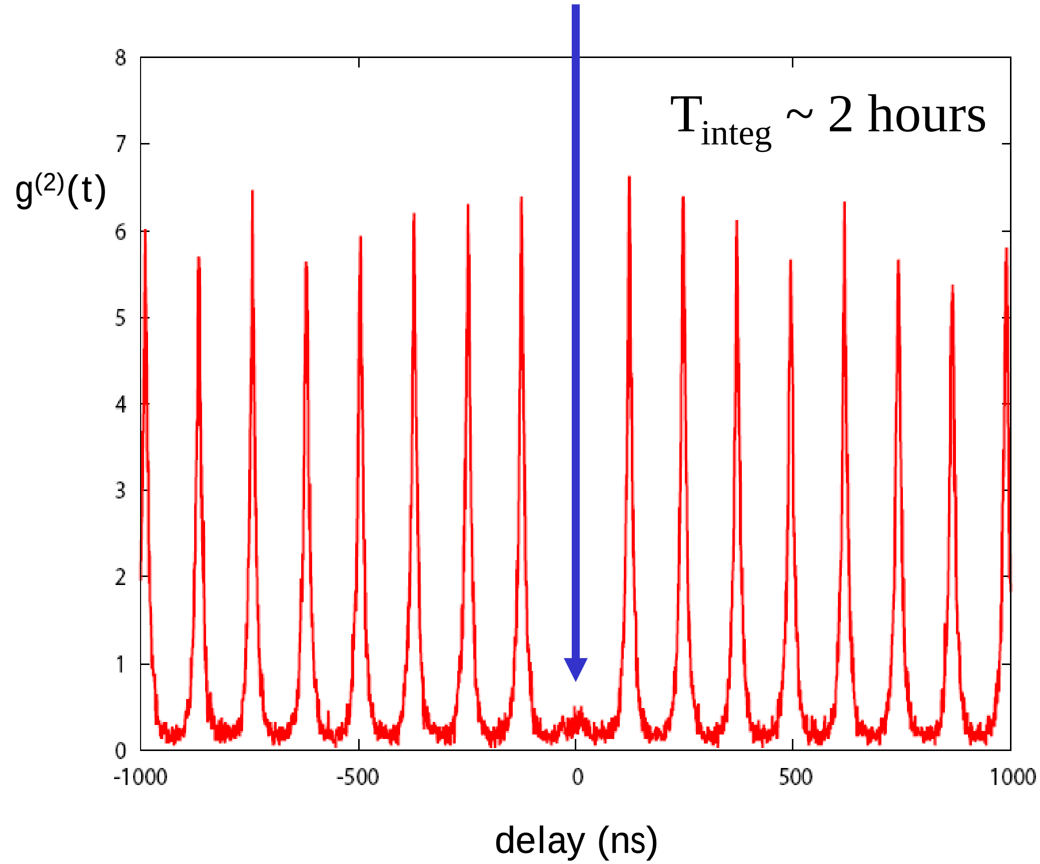


destructive interference of these paths

Y.H. Shih and C.O. Alley, Proc. 2nd Int'l Symp. Found. Quant. Mech, Tokyo (1986)
Hong, Ou, and Mandel, *Phys. Rev. Lett.*, **59**, 2044 (1987)
Y.H. Shih and C.O. Alley, *Phys. Rev. Lett.* **61**, 2921 (1988)

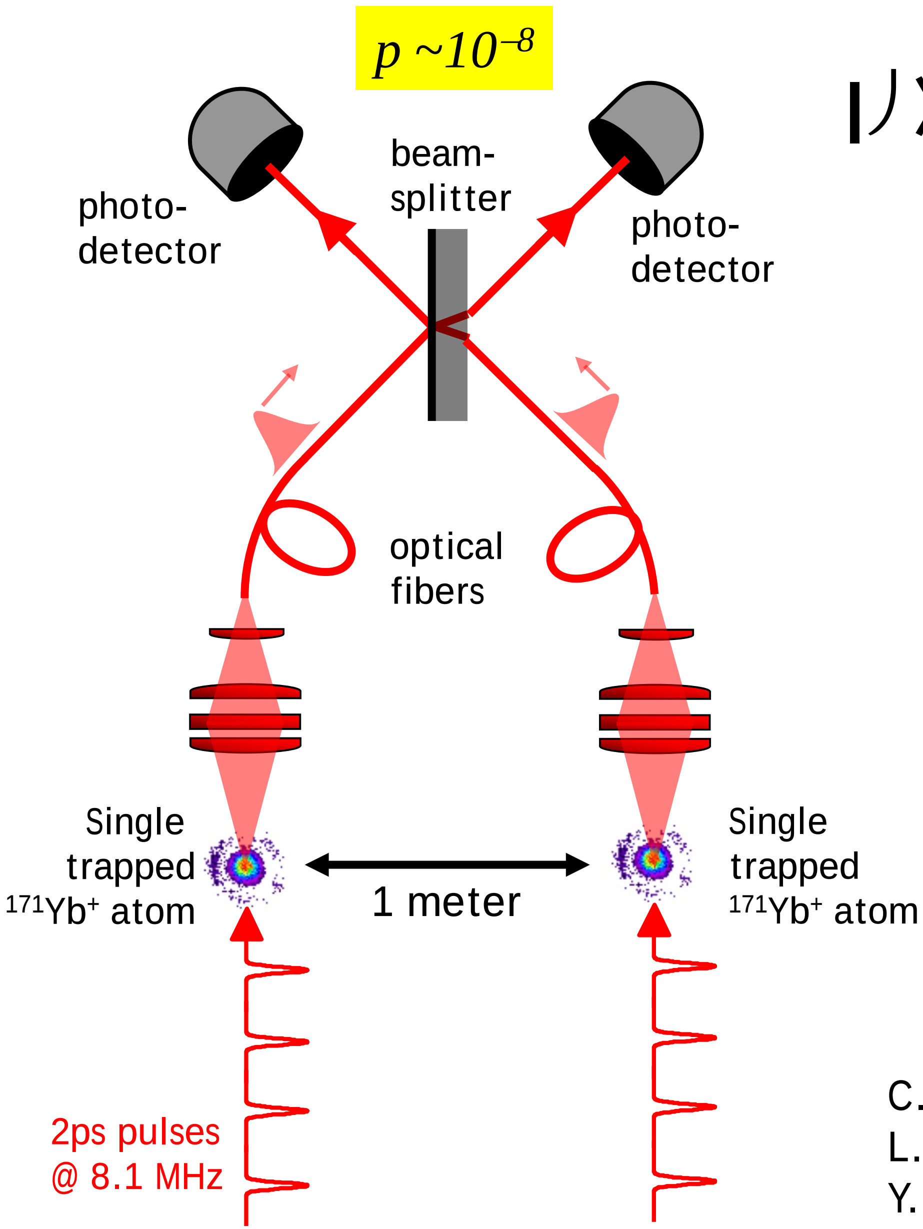


Quantum interference from two independent photons



Hong, Ou, Mandel, PRL 59, 2044 (1987)
Santori, et al., Nature, 419, 594 (2002)
Kaltenbaek, et al, PRL, 96, 240502 (2006)
Legero, et al., PRL, 93, 070503 (2004).
Thompson, et al., Science, 313, 74 (2006).
Felinto, et al. Nature Physics, 2, 844 (2006).
Beugnon, et al. Nature, 440, 779 (2006).
P. Maunz, et al., Nature Physics 3, 538 (2007)

Now with odd isotopes (having nuclear spin)



$$|\Psi\rangle = (|\downarrow\rangle_1 |\text{blue}\rangle_1 + |\uparrow\rangle_1 |\text{red}\rangle_1) \otimes (|\downarrow\rangle_2 |\text{blue}\rangle_2 + |\uparrow\rangle_2 |\text{red}\rangle_2)$$

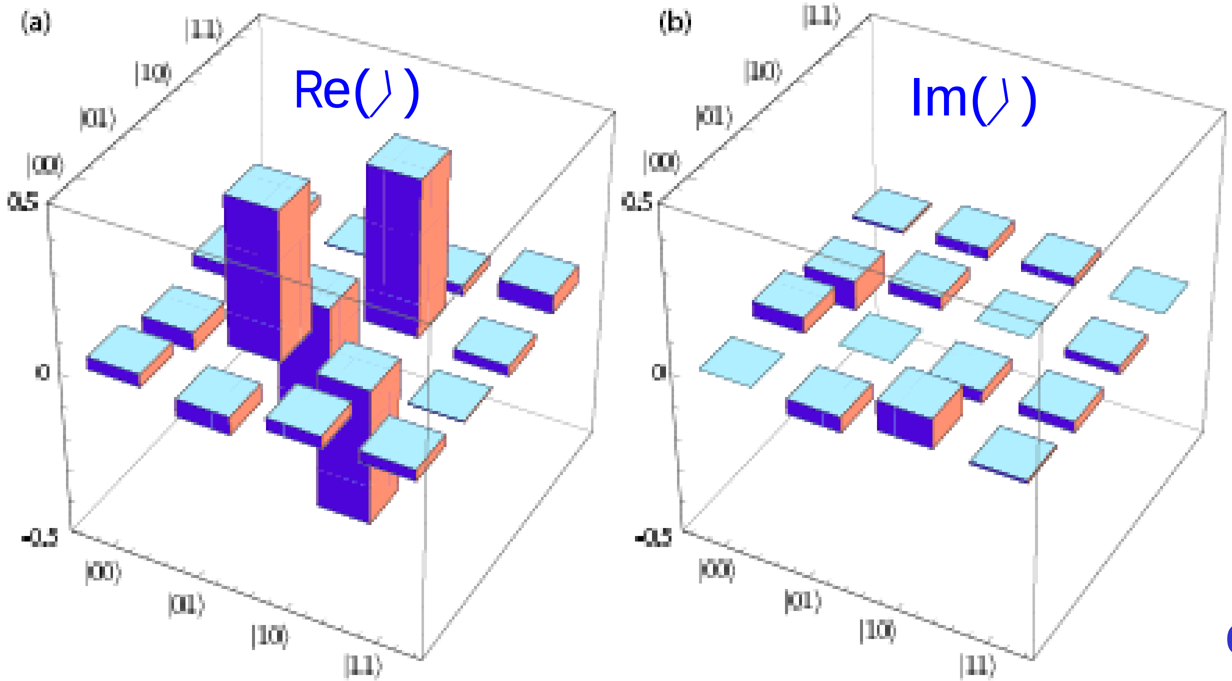
$$\Rightarrow |\downarrow\rangle_1 |\uparrow\rangle_2 - |\uparrow\rangle_1 |\downarrow\rangle_2$$

...upon coincidence photon detection

insensitive to
- interferometric phase noise
- ion motion

C. Simon and W. Irvine, PRL **91**, 110405 (2003)
L.-M. Duan, et. al., *Quant. Inf. Comp.* **4**, 165 (2004)
Y. L. Lim, et al., PRL **95**, 030505 (2005)

Full tomography of entangled state
(rotate qubits before measurement)



Fidelity **F = 0.87**

Concurrence **C = 0.77**

Entanglement of Formation **E = 0.69**

Bell Signal **S = 2.22 ± 0.07** (28 hours)

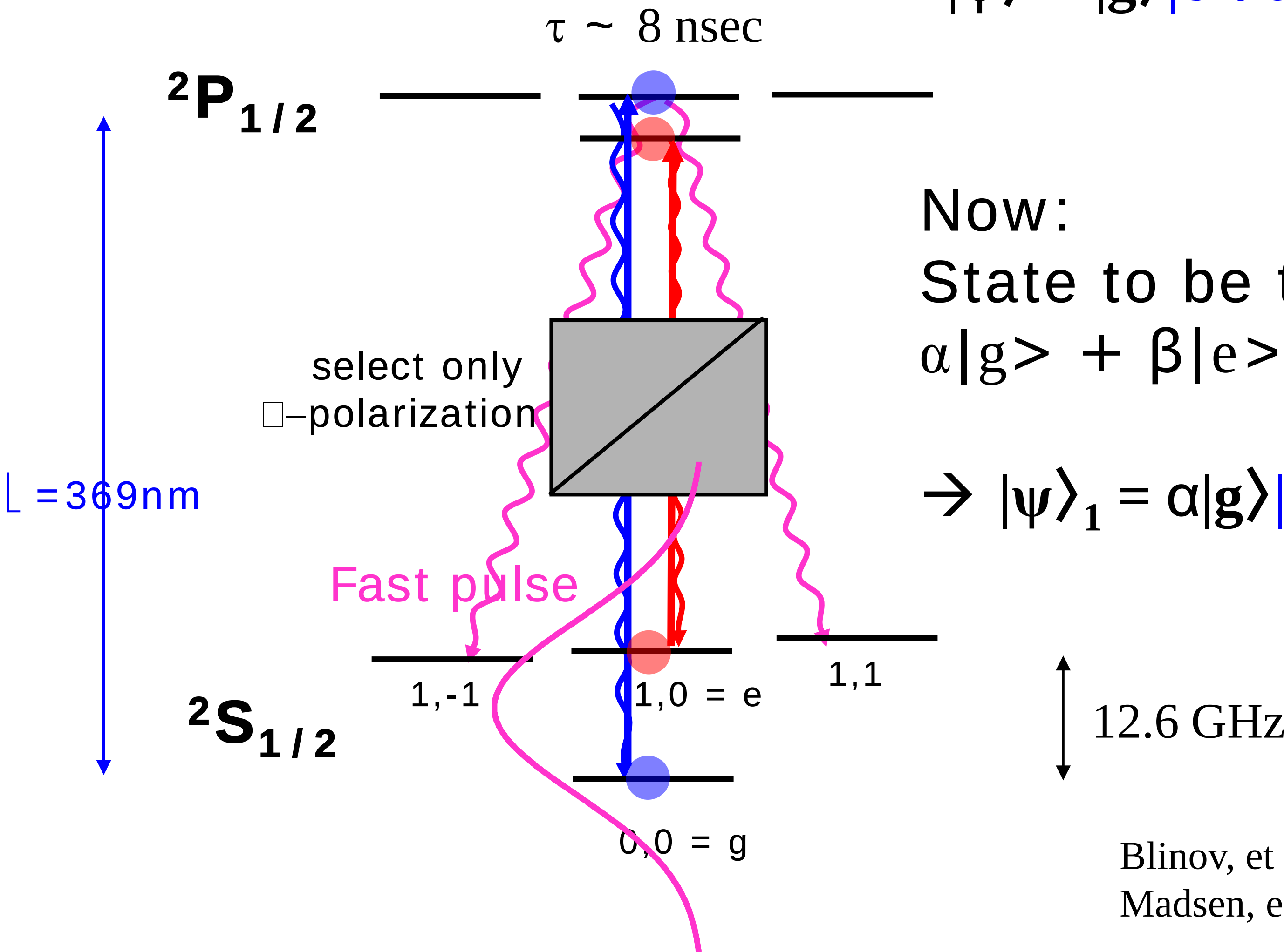
Bell Signal **S = 2.77 ± 0.20** **(new)**

D. Moehring, et al., Nature **449**, 68 (2007)
D. Matsukevich, et al., PRL **100**, 150404 (2008)

Teleportation

$^{171}Yb^{+}$

Before:
Equal superposition of |g> and |e>
→ $|\psi\rangle = |g\rangle|\text{blue}\rangle + |e\rangle|\text{red}\rangle$

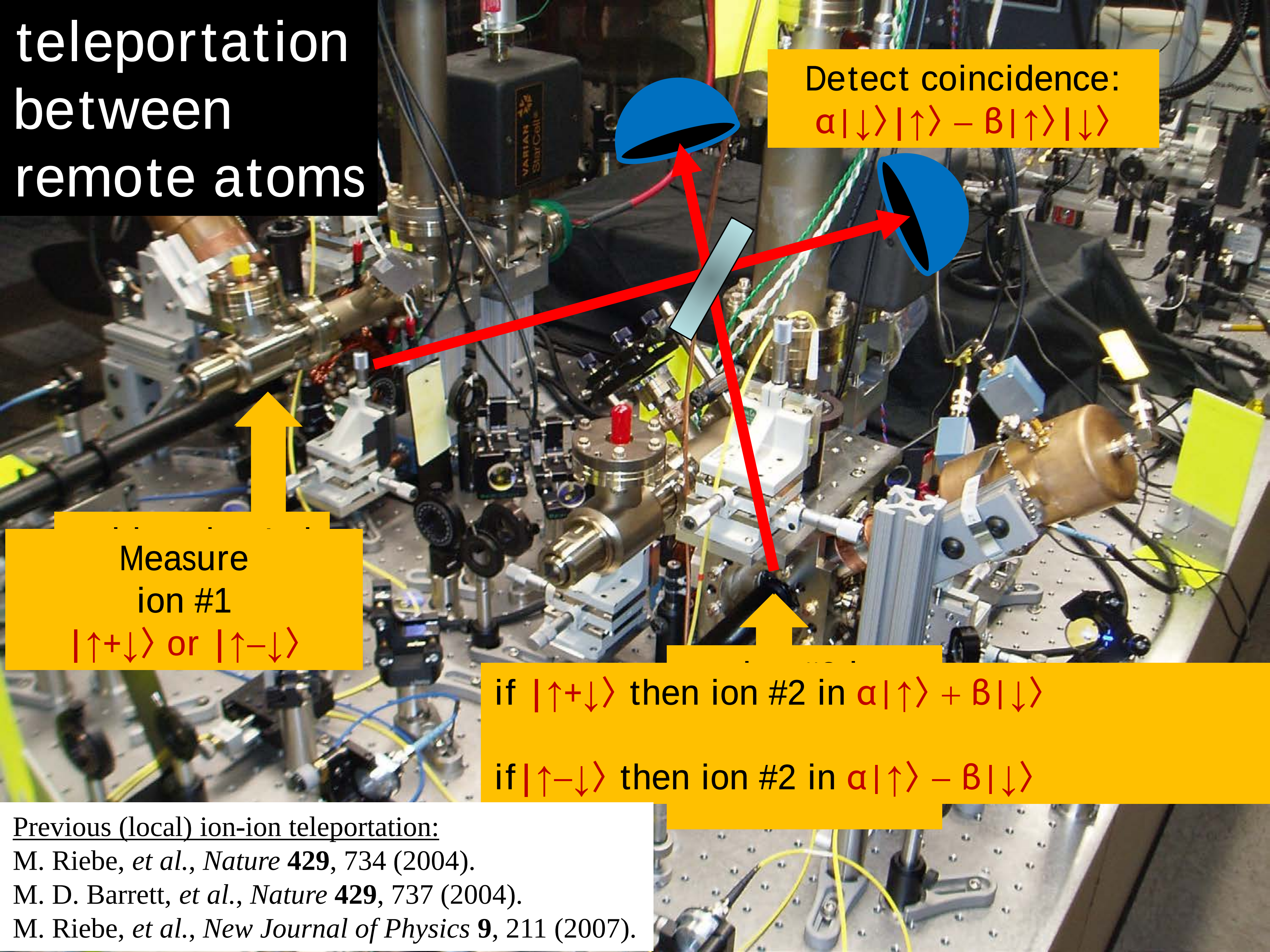


Now:
State to be teleported:
α|g> + β|e>

→ $|\psi\rangle_1 = \alpha|g\rangle|\text{blue}\rangle + \beta|e\rangle|\text{red}\rangle$

Blinov, et al., *Nature* **428**, 153 (2004)
Madsen, et al., PRL **97** 040505 (2006)

teleportation between remote atoms



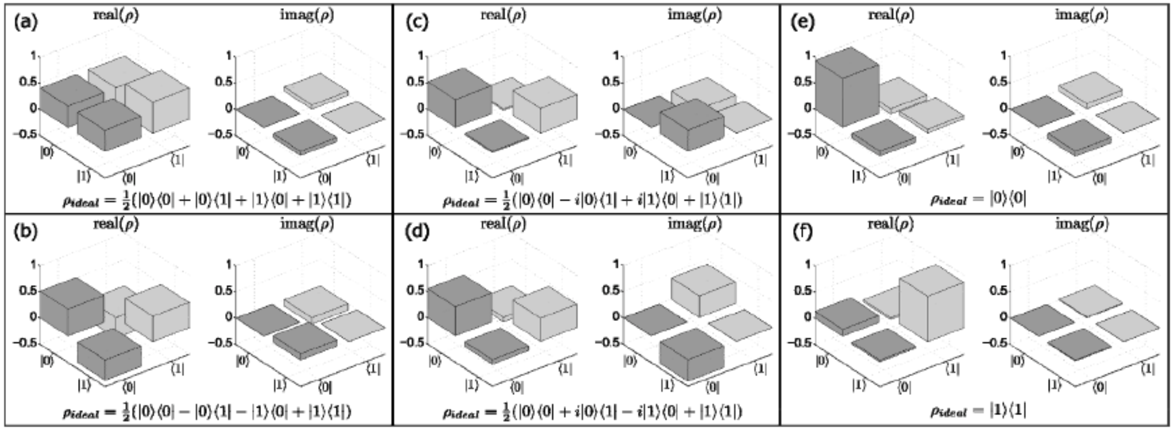
<u>Previous (local) ion-ion teleportation:</u>

M. Riebe, *et al.*, *Nature* **429**, 734 (2004).

M. D. Barrett, *et al.*, *Nature* **429**, 737 (2004).

M. Riebe, *et al.*, *New Journal of Physics* **9**, 211 (2007).

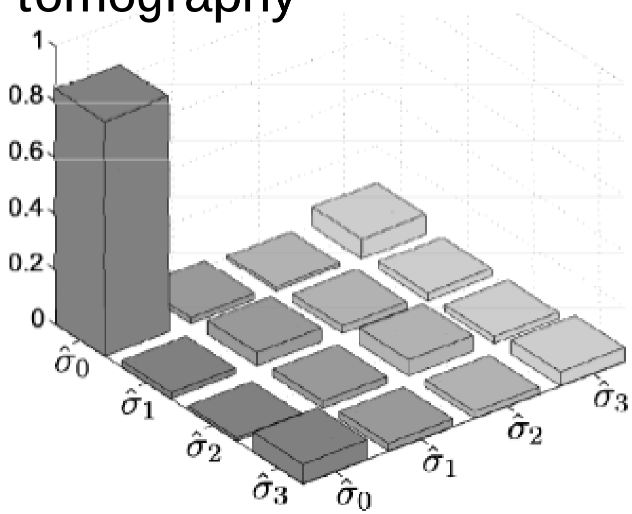
tomography of teleported state



State Teleported	Fidelity
$\lvert\downarrow\rangle$	0.93(4)
$\lvert\uparrow\rangle$	0.88(4)
$\lvert\downarrow\rangle + \lvert\uparrow\rangle$	0.91(3)
$\lvert\downarrow\rangle - \lvert\uparrow\rangle$	0.88(4)
$\lvert\downarrow\rangle + i\lvert\uparrow\rangle$	0.92(4)
$\lvert\downarrow\rangle - i\lvert\uparrow\rangle$	0.91(4)

⟨Fidelity⟩ > 0.90

teleportation process tomography



S. Olmschenk, et al. Science ***323****, 486 (2009)*

1 bit: 12 minutes

1500 events = 300 hours

Probability of heralding per attempt

probability of 1 photon emitted and detected

Prob. of having singlet Bell state

$$p = \frac{1}{4}\left[(0.995)(0.8)(0.95)(0.2)(0.15)(0.02)\right]^2 = 6\times 10^{-8}$$

branching to $^2D_{3/2}$ state

losses

excitation probability

fiber coupling efficiency

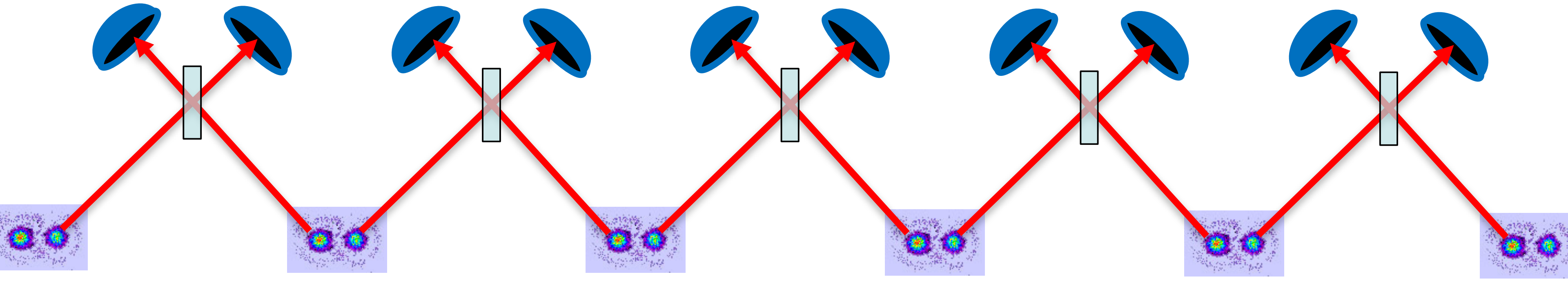
detector efficiency

solid angle

Rate of heralded entanglement

$R = \Gamma p = 0.04/sec$

Quantum networking with probabalistic entanglement



Quantum repeaters

Briegel *et al.*, PRL **81**, 5932 (1998)

Distributed quantum computing with hybrid gates

Duan, et al., Quant. Inf. Comp. 4, 165 (2004)

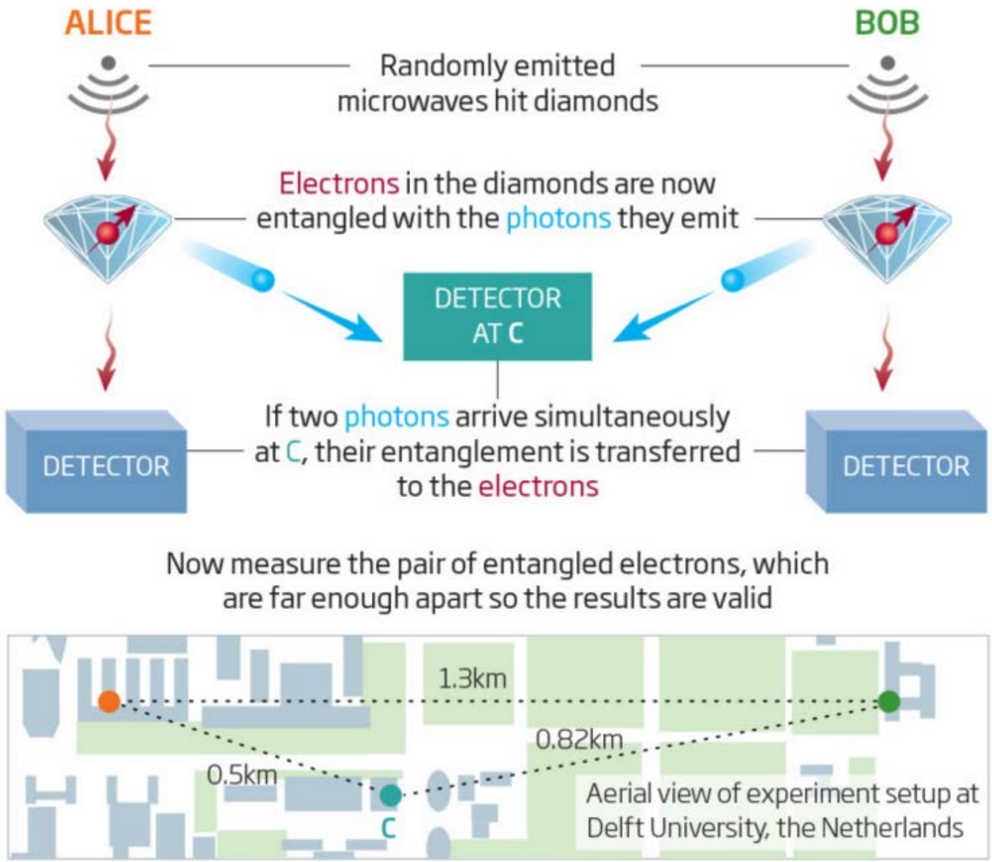
Connection time: $\tau \sim \dfrac{\log N}{p}$

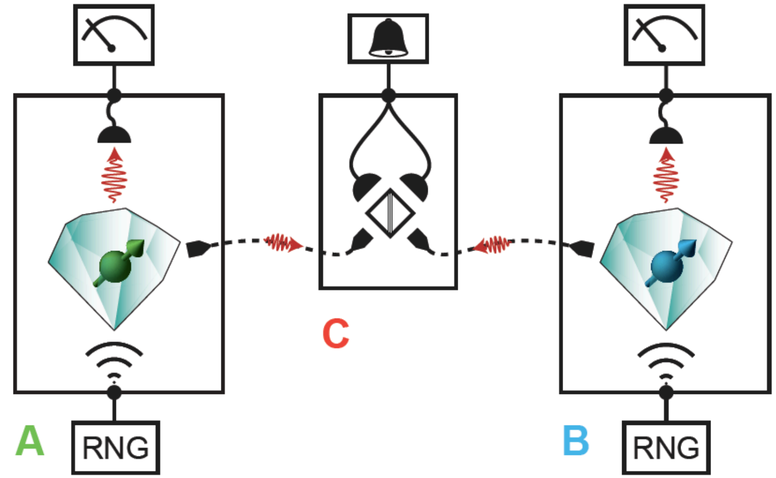
Need to use multiplexing → try many modes (e.g., frequency, spatial, time-bin) simultaneously to establish connection between each set of nodes.

Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres

Nature **526**, 682–686 (29 October 2015)

B. Hensen, H. Bernien, A. E. Dréau, A. Reiserer, N. Kalb, M. S. Blok, J. Ruitenberg, R. F. L. Vermeulen, R. N. Schouten, C. Abellán, W. Amaya, V. Pruneri, M. W. Mitchell, M. Markham, D. J. Twitchen, D. Elkouss, S. Wehner, T. H. Taminiau & R. Hanson





Detection rate:

245 trials over a system runtime of **220 hours**.

P-value: 0.04 (~ 2 σ)

(p-value is the probability that local realism would produce results at least as extreme as those measured)

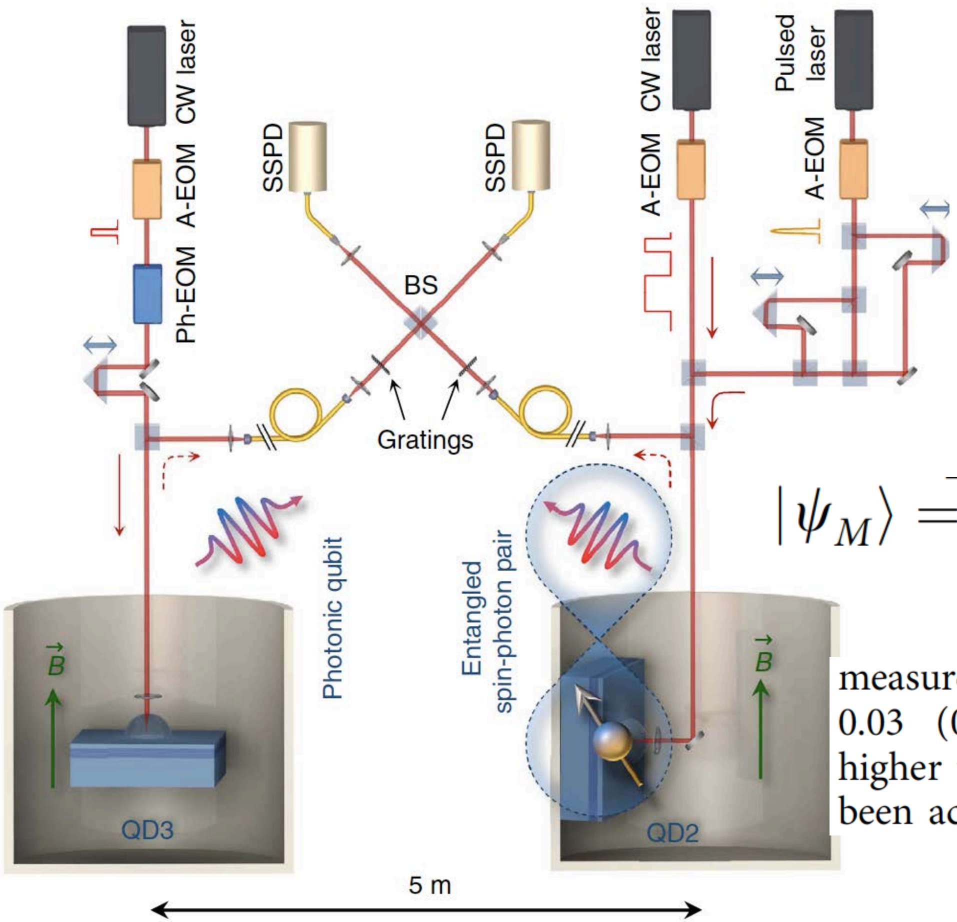
ARTICLE

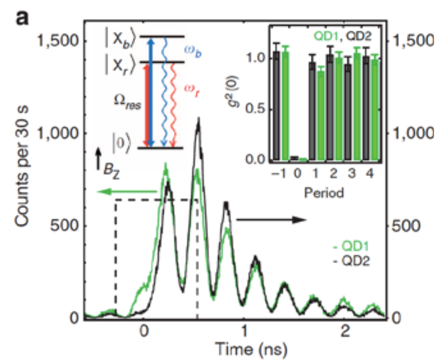
Received 8 Jul 2013 | Accepted 9 Oct 2013 | Published 1 Nov 2013

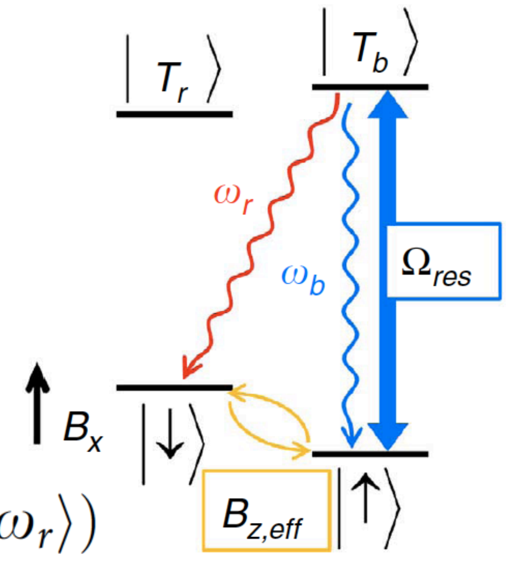
nature COMMUNICATIONS

Quantum teleportation from a propagating photon to a solid-state spin qubit

W.B. Gao[1], P. Fallahi[1], E. Togan[1], A. Delteil[1], Y.S. Chin[1], J. Miguel-Sanchez[1] & A. Imamoğlu[1]







$$|\psi_M\rangle = (1/\sqrt{2})(|\omega_b\rangle + |\omega_r\rangle)$$

$$= 80.2 \pm 2.9 \ \%$$

measurements, we obtain the teleported state fidelities 0.76 ± 0.03 (0.75 ± 0.03) for $|\omega_r\rangle_A + |\omega_b\rangle_A (|\omega_r\rangle_A - |\omega_b\rangle_A)$. Slightly higher teleportation state fidelities 0.80 ± 0.03 (0.78 ± 0.03) have been achieved in the case without the spin-echo pulse sequence

three-fold coincidence rate $19\,h^{-1}$