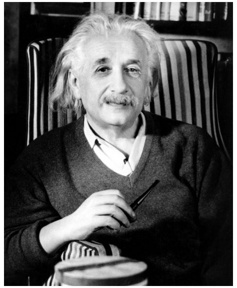
Physics of Quantum Information

Lecture 3: Entanglement (I)

The Einstein – Bohr debate: a philosophical one?



A. Einstein

Measure on A can not influence the one on B = **LOCALITY**

$\Rightarrow$ correlations possible only if the two photons share a **common property** which determines their state before the measurement

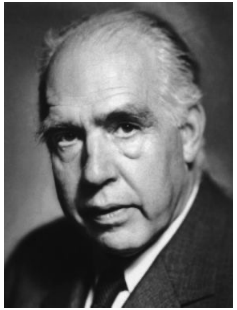
But… No such property in quantum theory

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)



N. Bohr

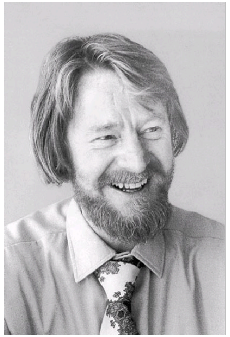
Photons have no defined polarization state before the measurement

Correlation = intrinsic property of the state

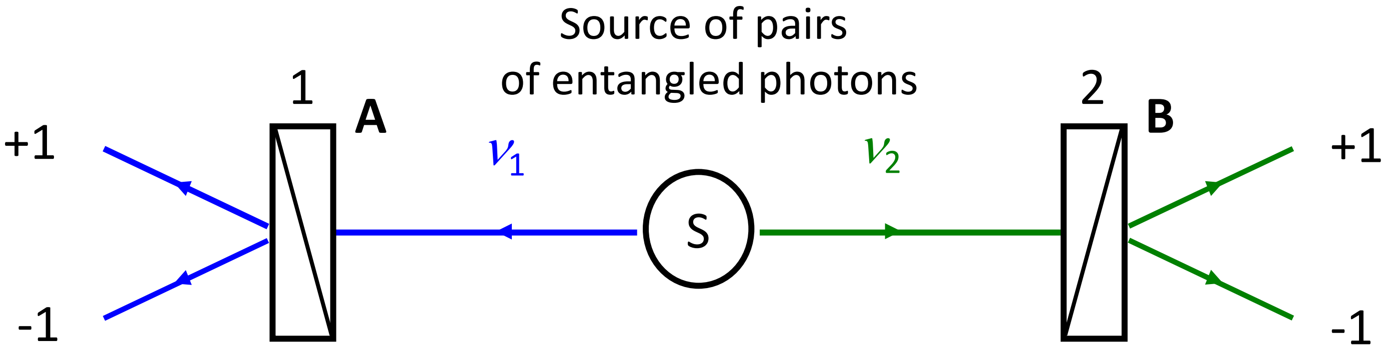
Polarisation state **fixed when measuring** **(Random result)**

Quantum physics is **complete** !

John Bell (1964): philosophical debate testable experimentally



John Bell
(1938 - 1990)



Two orientations $\mathbf{A_1}$, $\mathbf{A_2}$ & $\mathbf{B_1}$, $\mathbf{B_2}$ of each polarizer

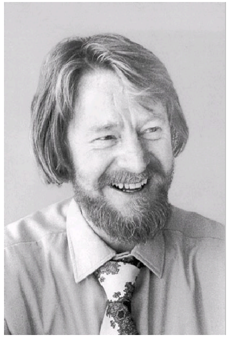
Measure $S = \langle \mathbf{A}_1 (\mathbf{B}_1 + \mathbf{B}_2) \rangle + \langle \mathbf{A}_2 (\mathbf{B}_1 - \mathbf{B}_2) \rangle$

Einstein : hidden variable λ determines outcome of measurement

$\mathbf{A}_1(\lambda), \mathbf{A}_2(\lambda), \mathbf{B}_1(\lambda), \mathbf{B}_2(\lambda) = \pm 1 \quad \Rightarrow \quad -2 \leq S \leq 2$

Quantum Physics predicts $S > 2$ for some orientations

John Bell (1964): philosophical debate testable experimentally



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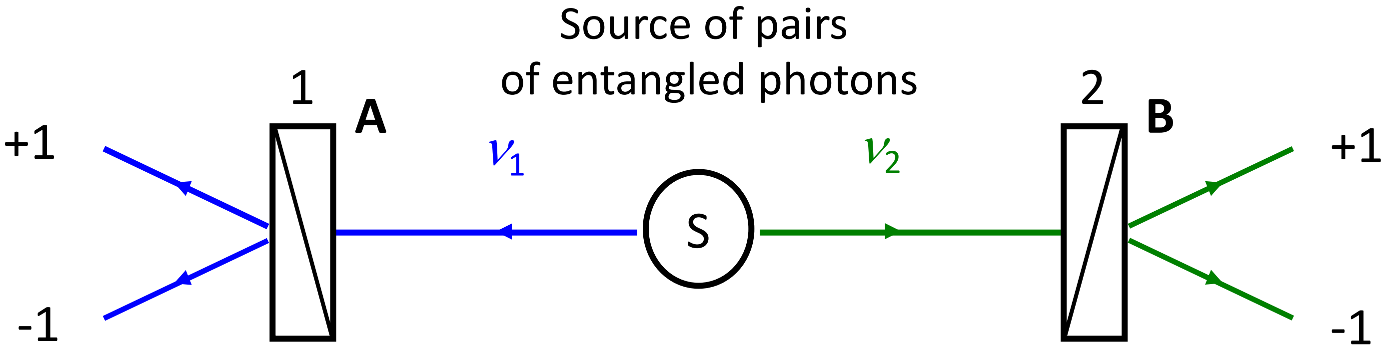

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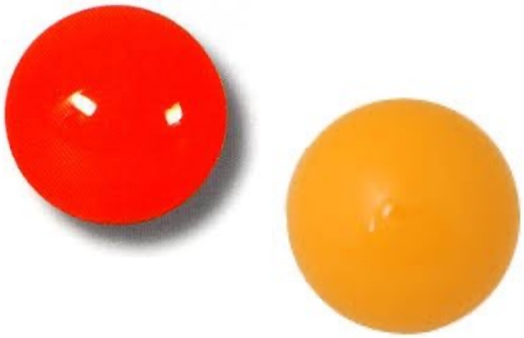
Quantum Physics predicts $S > 2$ for some orientations

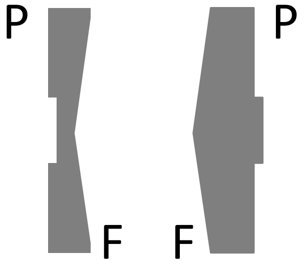
Strong correlations also exist in the classical world…

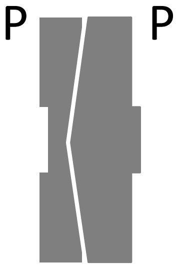


Entanglement ⇒ **RJ, JR, RJ, RJ, JR…**

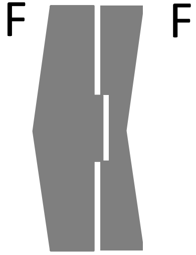
Entanglement ⇒ **PP, FF, FF, PP, PP, FF, …**

Correlations may be explained by the **random fluctuations** of a hidden « mechanism »

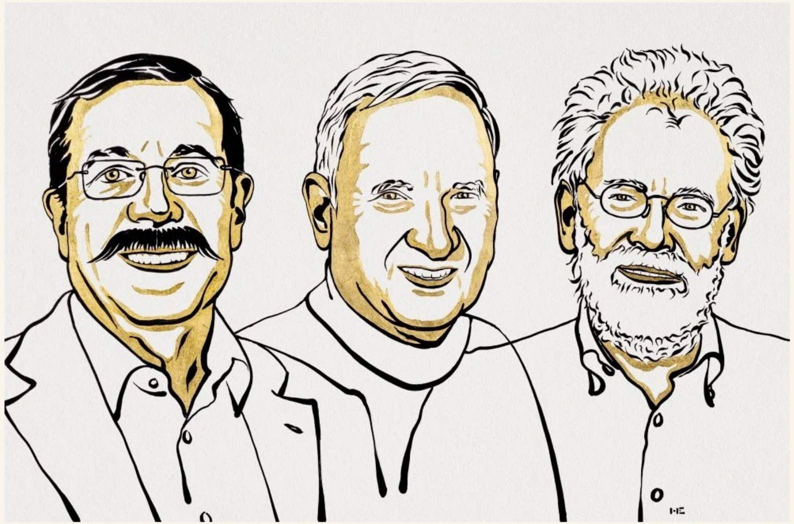




OR



The Nobel Prize in Physics 2022



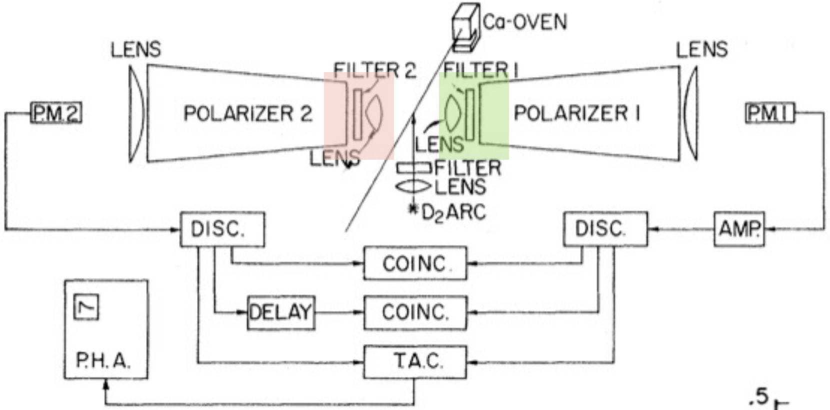
Ill. Niklas Elmehed © Nobel Prize Outreach

The Nobel Prize in Physics 2022 was awarded jointly to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with *entangled* photons, establishing the *violation of Bell inequalities* and pioneering *quantum information* science"

The first conclusive test: John Clauser

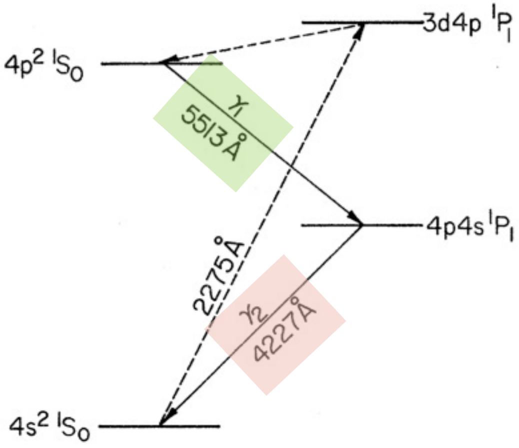
John Clauser

Phys. Rev. Lett. 1972

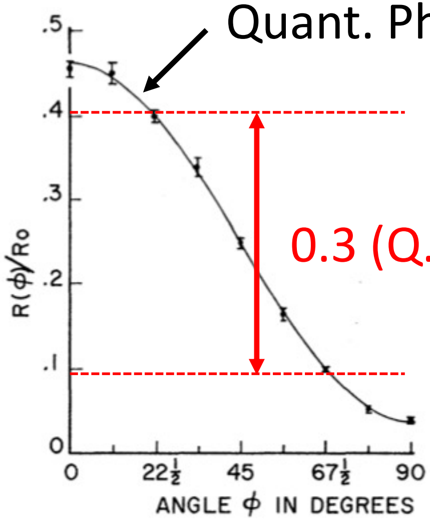


Single-photon source: radiative cascade ^{40}Ca

$$\frac{1}{\sqrt{2}}(|h_1, h_2\rangle + |v_1, v_2\rangle)$$



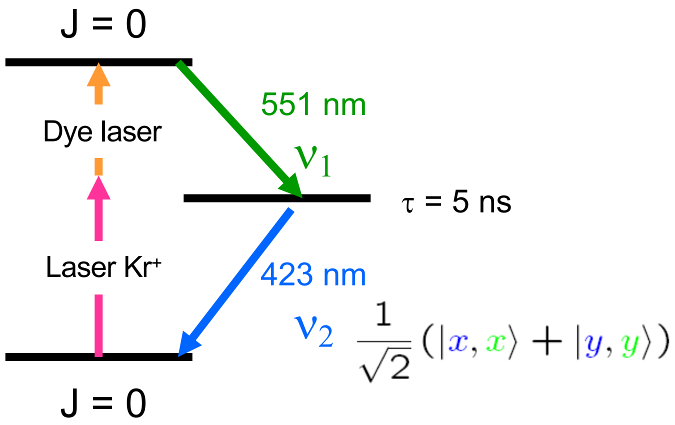
Quant. Phys.



0.3 (Q.) > 0.25 (cl.)

The Aspect's experiments (Orsay 1974 - 1982): exp. 1

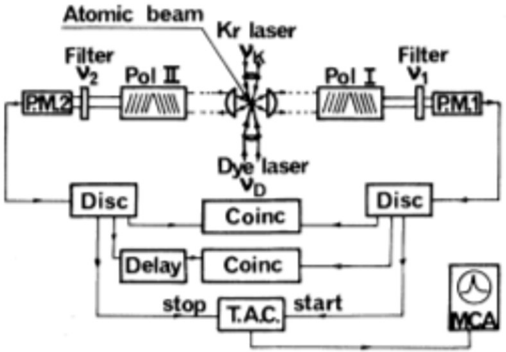
Radiative cascade Ca

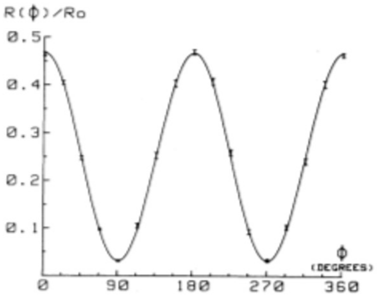


A new source of entangled photons

Aspect, Grangier & Roger, Phys. Rev. Lett. **47**, 460 (1981)

Higher flux $\Rightarrow$ better statistics





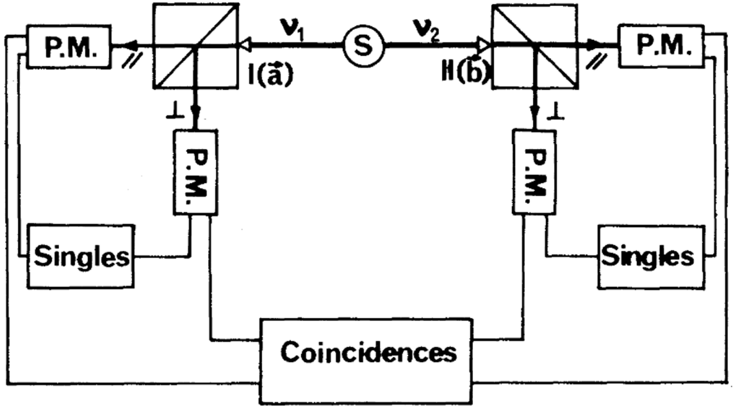
$$\delta_{exp} = 0.0572 \pm 0.0043$$

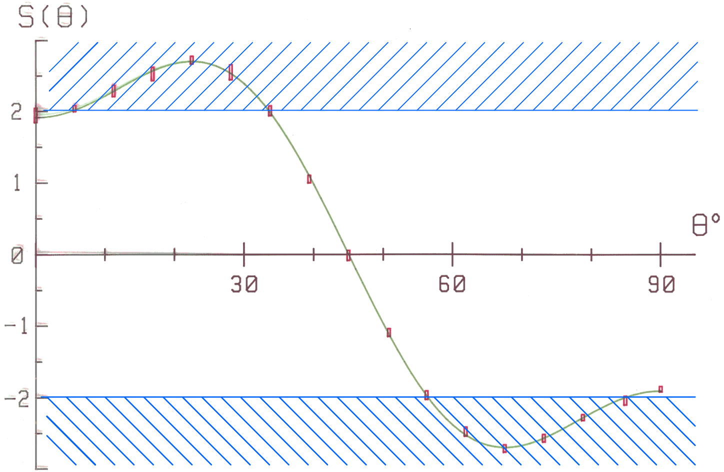
Violation by 10 standard deviations

The Aspect's experiments (Orsay 1974 - 1982): exp. 2

Aspect, Grangier & Roger, Phys. Rev. Lett. **49**, 91 (1982)

Two-channel detectors





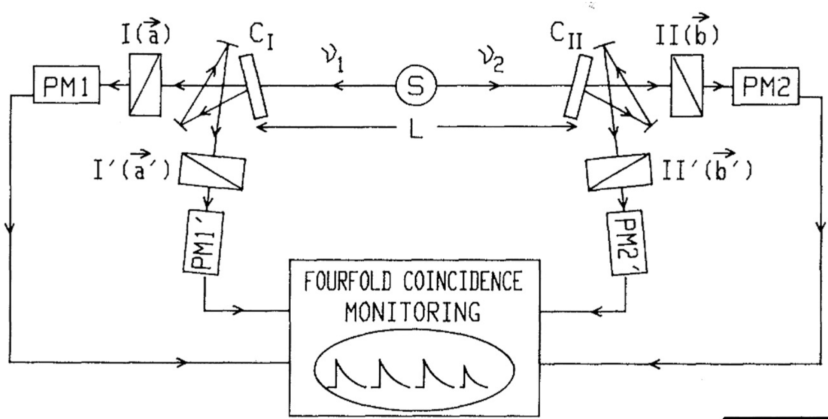
$$-2 \leq S_{Bell} \leq 2$$

$$S_{QM}(\theta = 22.5°) \leq 2.70 \pm 0.05$$
$$S_{exp}(\theta = 22.5°) \leq 2.697 \pm 0.015$$

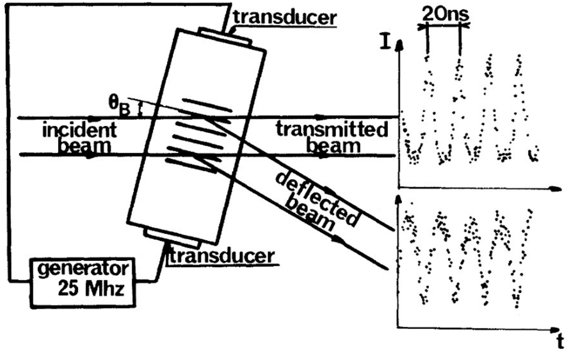
The Aspect's experiments (Orsay 1974 - 1982): exp. 3

Aspect, Dalibard & Roger, Phys. Rev. Lett. **49**, 1804 (1982)

Test of non-locality



$-1 \leq S'_{Bell} \leq 0$ (Shimony-Holt inequality)

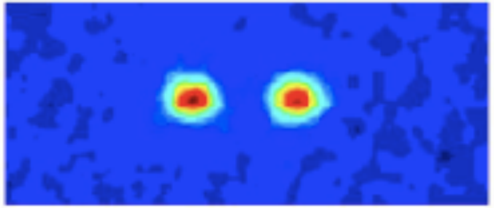


$$S'_{QM}(\theta = 22.5°) = 0.112$$
$$S'_{exp}(\theta = 22.5°) = 0.101 \pm 0.020$$

And since then…

2001: 2 ions

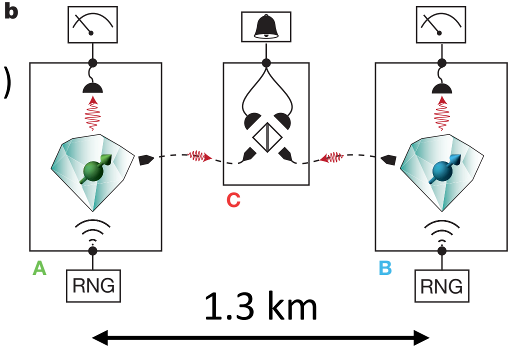
Wineland (USA)

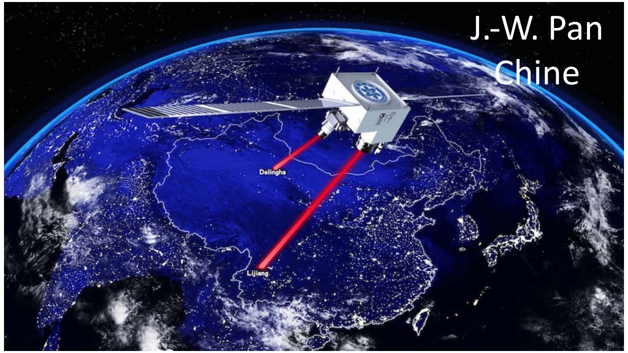


2015: « loophole-free » tests

Zeilinger (Autriche)

Hanson (Pays-bas)
Shalm (USA)

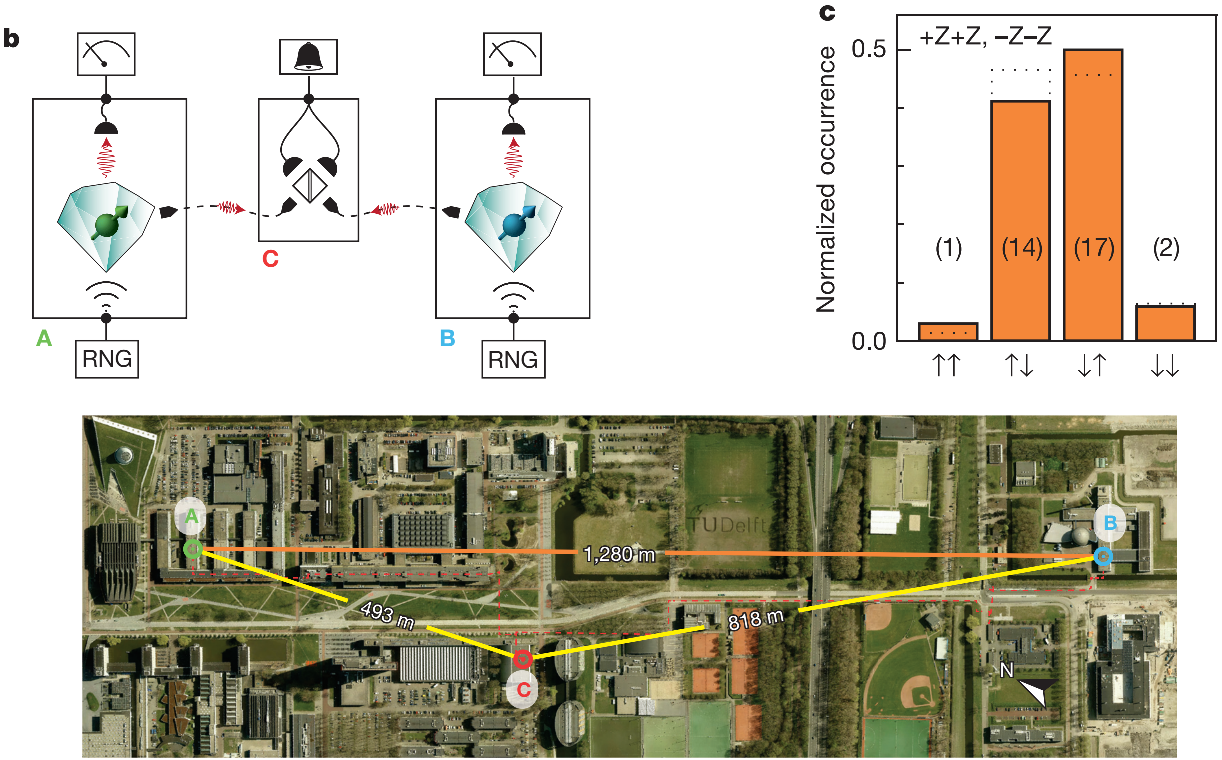




2017: sources in satellite
D = 1200 km

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

B. Hensen[1,2], H. Bernien[1,2]†, A. E. Dréau[1,2], A. Reiserer[1,2], N. Kalb[1,2], M. S. Blok[1,2], J. Ruitenberg[1,2], R. F. L. Vermeulen[1,2], R. N. Schouten[1,2], C. Abellán[3], W. Amaya[3], V. Pruneri[3,4], M. W. Mitchell[3,4], M. Markham[5], D. J. Twitchen[5], D. Elkouss[1], S. Wehner[1], T. H. Taminiau[1,2] & R. Hanson[1,2]



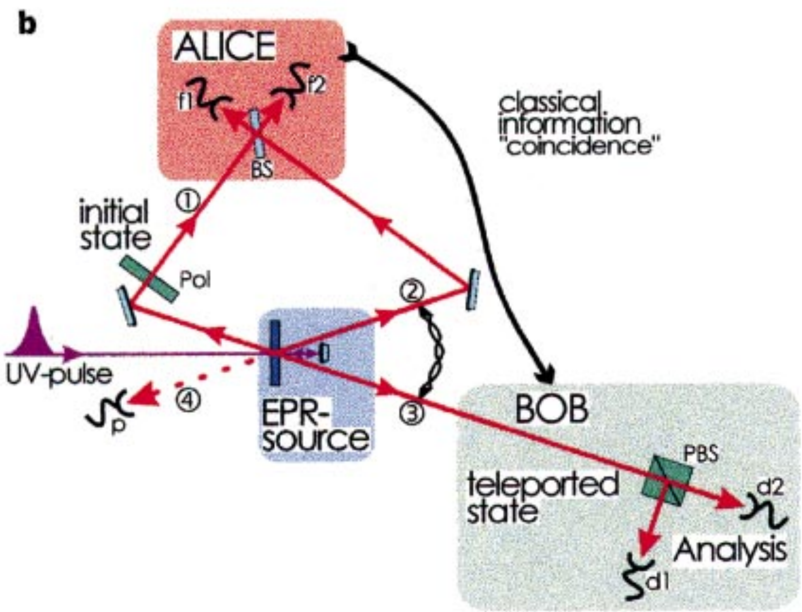
Quantum teleportation with photons

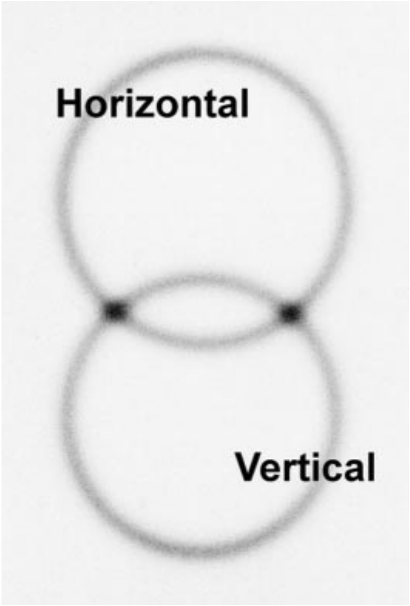
Experimental quantum teleportation

Nature 1997

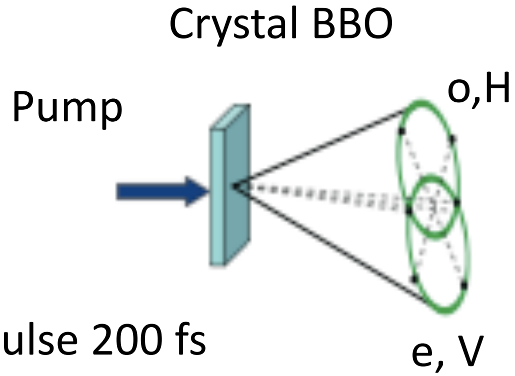
Dik Bouwmeester, Jian-Wei Pan, Klaus Mattle, Manfred Eibl, Harald Weinfurter & Anton Zeilinger

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

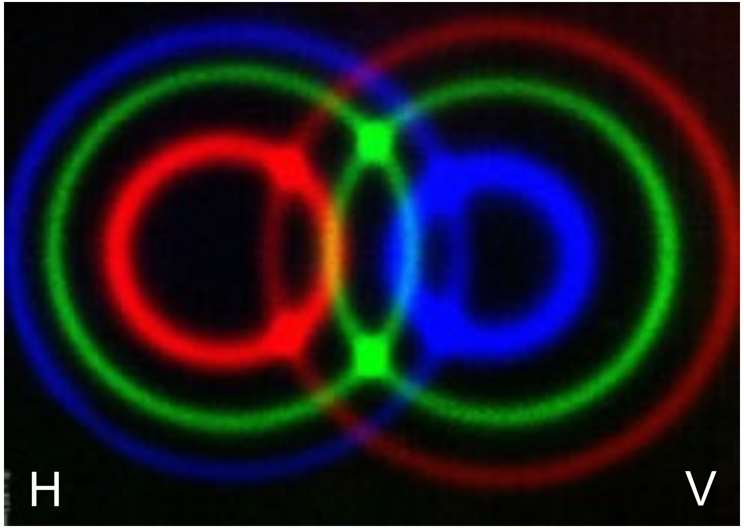




Spontaneous parametric downconversion (type II)



Pulse 200 fs
395 nm, 76 MHz



Proba to create 1 pair ~ 10^{-2}

$$\frac{1}{\sqrt{2}}(|H,V\rangle + |V,H\rangle)$$

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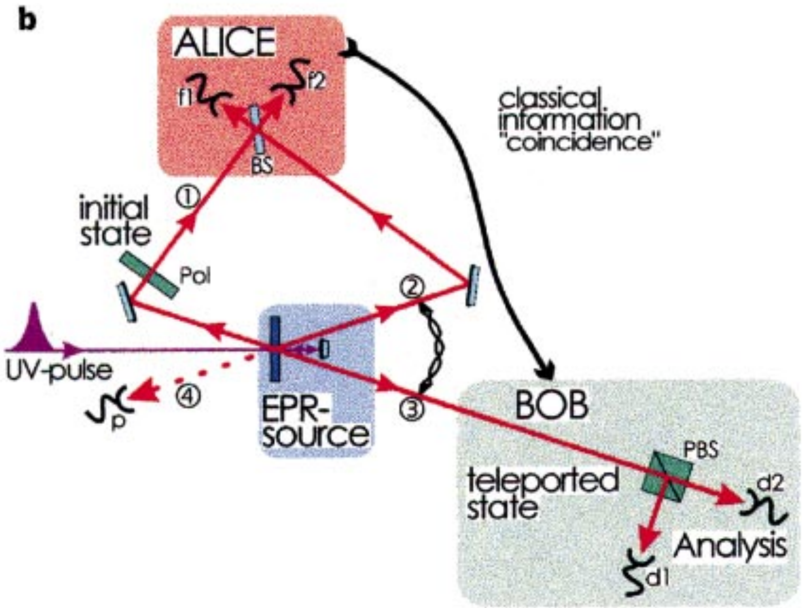
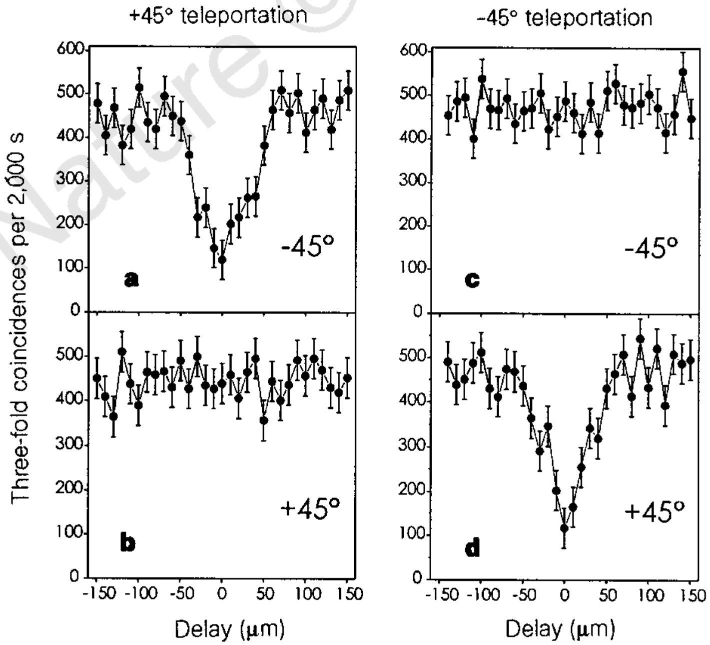




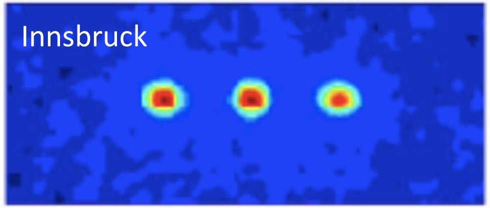
Quantum teleportation with ions (Nature 2005)

Deterministic quantum teleportation of atomic qubits

M. D. Barrett[1]*, J. Chiaverini[1], T. Schaetz[1], J. Britton[1], W. M. Itano[1], J. D. Jost[1], E. Knill[2], C. Langer[1], D. Leibfried[1], R. Ozeri[1] & D. J. Wineland[1]

Quantum teleportation[1] provides a means to transport quantum information efficiently from one location to another, without the physical transfer of the associated quantum-information carrier.

$^{9}Be^{+}$



$$\alpha|\uparrow\rangle + \beta|\downarrow\rangle$$

Deterministic quantum teleportation with atoms

M. Riebe[1], H. Häffner[1], C. F. Roos[1], W. Hänsel[1], J. Benhelm[1], G. P. T. Lancaster[1], T. W. Körber[1], C. Becher[1], F. Schmidt-Kaler[1], D. F. V. James[2] & R. Blatt[1,3]

$^{40}Ca^{+}$