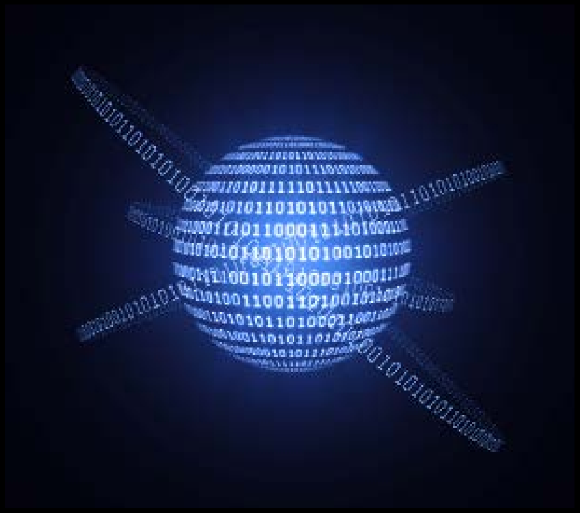
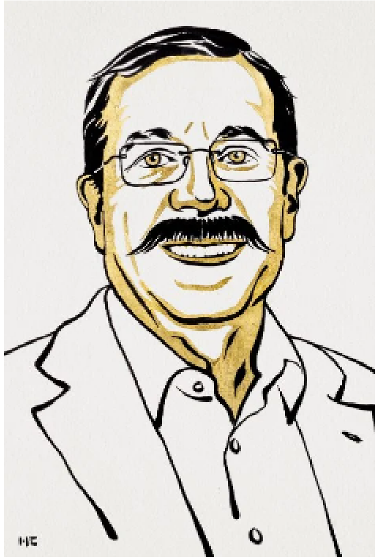
Entanglement



Marco Genovese

INRIM

The Nobel Prize in Physics 2022



Ill. Niklas Elmehed © Nobel Prize Outreach

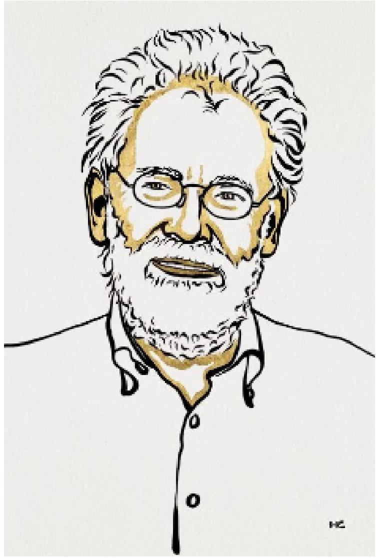
Alain Aspect

Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

John F. Clauser

Prize share: 1/3



Ill. Niklas Elmehed © Nobel Prize Outreach

Anton Zeilinger

Prize share: 1/3

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"

In the last years the experimental know-how concerning creation and manipulation of quantum systems has hugely increased, permitting the realisation of several experiments originally thought as Gedanken Experiment and the conceiving of new ones.

The dream of testing the theoretical ideas proposed in connection with foundations of quantum mechanics become reality.

-Tests of local realism

-Experiments on the transition from quantum to classical world

New fields of research related to these achievements:

Quantum Technologies

Superposition principle

$c_1 \mid ½ > \; + c_2 \mid - ½ >$

$c_1 \mid H > + c_2 \mid V >$

Many particles: entangled states

$$|S=0> = \frac{[(\mid ½ > \mid -½ > - \mid -½ > \mid ½ >)]}{\sqrt{(2)}}$$

$$|P=0> = \frac{[(\mid H > \mid V > - \mid H > \mid V >)]}{\sqrt{(2)}}$$

Is QM a complete theory?

Already in 1935 **Einstein, Podolsky, Rosen** posed the question if Quantum Mechanics can be considered a complete theory describing all the elements of reality or if it is just a statistical approximation of a realistic theory.

i) Element of Physical reality : If we can predict with certainty the value of an observable without disturbing the system

ii) No action at distance

$$|0\rangle = \frac{[(|H\rangle|V\rangle - |V\rangle|H\rangle)]}{\sqrt{(2)}} = \frac{[(|A\rangle|D\rangle - |D\rangle|A\rangle)]}{\sqrt{(2)}}$$

$|A\rangle = (|H\rangle+|V\rangle)/\sqrt{(2)}$ $|D\rangle = (|H\rangle-|V\rangle)/\sqrt{(2)}$

Quantum Non Locality compatible with special relativity

010001110 1110011110000

$$\frac{|H\rangle\,|V\rangle - |V\rangle\,|H\rangle}{\sqrt{2}}$$

010001110 1110011110000

In SMQ no superluminal communication [Ghirardi,Rimini,Weber LNC 27 (80) 293.]

$$W_{12} \to W'_{12} = \sum_s P_s^1 W_{12} P_s^1$$

The reduced trace is:

$$W_2 = Tr_1[W'_{12}] = Tr_1[\sum_k P_k^1 W_{12} P_k^1] = \sum_k Tr_1[P_k^1 W_{12} P_k^1]$$

By using trace properties:

$$W_2 = \sum_k Tr_1[P_k^1 W_{12} P_k^1] = \sum_k Tr_1[P_k^1 W_{12}] = Tr_1[\sum_k P_k^1 W_{12}] = Tr_1[W_{12}]$$

That is exactly the same reduced density operator
we would have obtained without any measurement

The measurement problem

The **von Neumann chain**:
(|a1>,|a2> quantum states,
|M0> initial state of detection apparatus
|M1>, |M2> final states of detection apparatus)

$$|a1>|M0> \rightarrow |a1>|M1>$$
$$|a2>|M0> \rightarrow |a2>|M2>$$

QM is linear:

$$\mathbf{(a\,|a1> + b\,|a2>)\,|M0> \rightarrow a\,|a1>|M1> + b\,|a2>|M2>}$$

The detection apparatus is entangled as well!!

Schrödinger cat paradox

$(a\,|a1\rangle + b\,|a2\rangle)\ |M0\rangle\,|cat\rangle$

$\rightarrow$

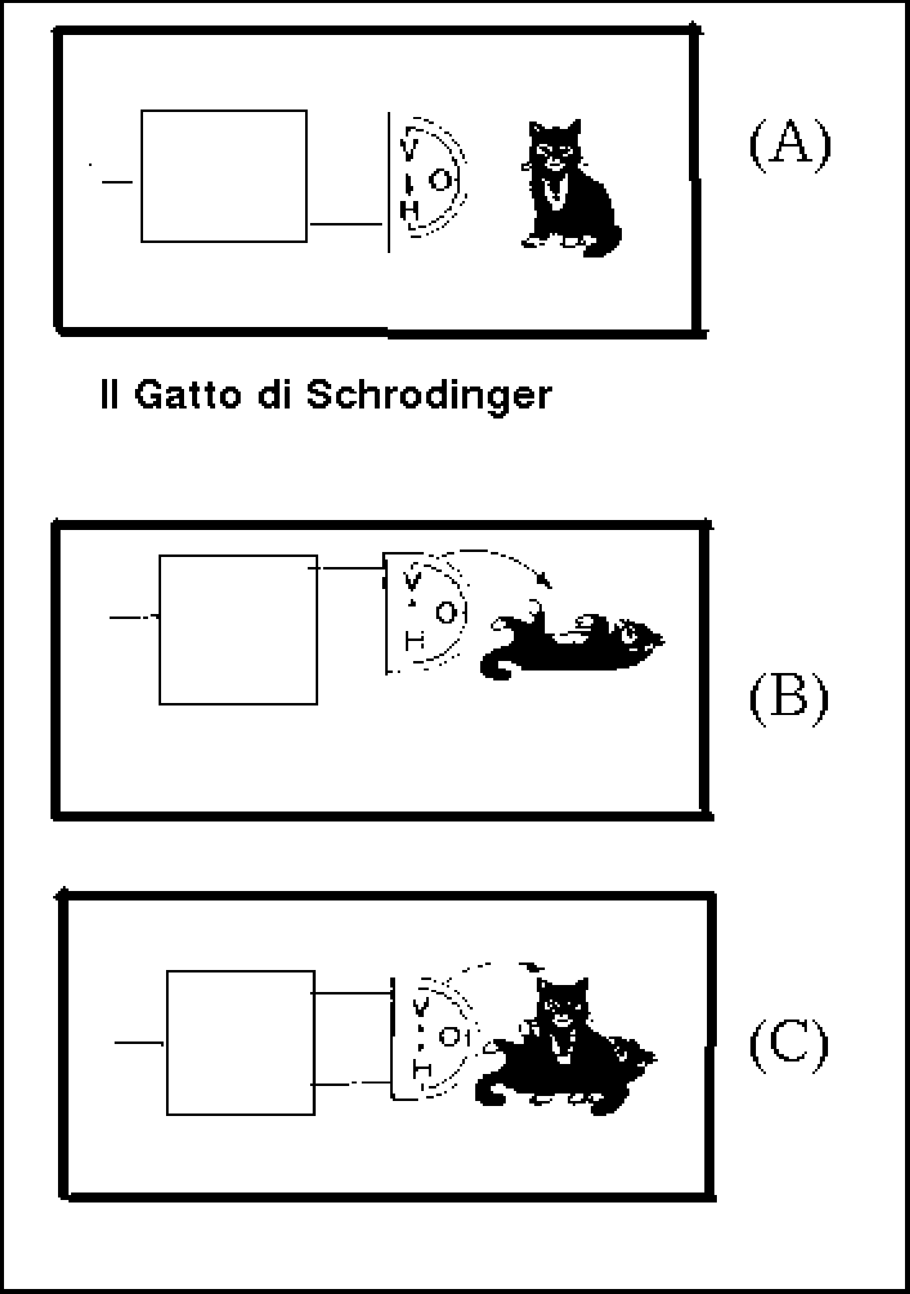
$(a\,|a1\rangle\,|M1\rangle +$

$b\,|a2\rangle|M2\rangle)\quad |cat\rangle$

$\rightarrow$

$a\,|a1\rangle\,|M1\rangle|cat\ alive\rangle +$

$b\,|a2\rangle|M2\rangle|dead\ cat\rangle$



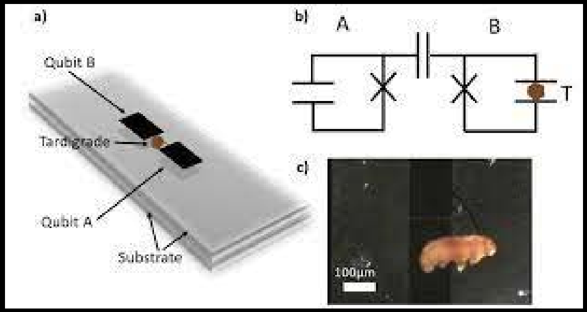
Some Schrödinger cat (kitten) :

-Entanglement of caesium gas samples (10^{12} atomi) [Julsgaard et al., Nature 413 (01) 400]

-Superconductors

-squids [Friedman et al., Nature 406 (00) 43]

-Tardigrade!! arXiv:2112.07978



-Entanglement transmitted from photons to Plasmons (10^{10} electrons) and back to photons [Altewischer et al., Nature 304 (02) 418]

Hopes to have hints on macro-objectivation at work from these systems…

Possible ways out of macro-objectivation problem:

measurements in quantum mechanics would seem to require some process breaking the entanglement: among the possible outcomes only one will be realised and observed in the measurement process. Only one state in the superposition survives the measurement process

A first answer is to split the world into a macroscopic one following classical mechanics and a microscopic one following QM (substantially the one adopted by the Copenaghen school). However this solution, even if perfectly useful for practical calculations of quantum processes, is weak from a conceptual point of view since it does not permit to identify the border between quantum and classical worlds. How many particles should a body have for being macroscopic? What about "macroscopic" systems as superconductors, which exhibit quantum properties?

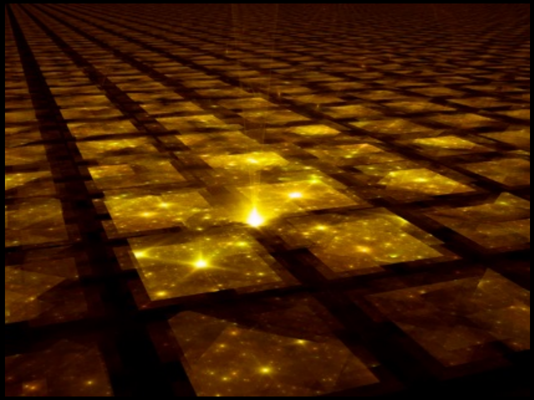
Various different ideas have been considered for explaining/understanding decoherence at macroscopic level, without reaching for any of them a general consensus in the physicists community. Among them:

- QM is the fundamental theory: the many universes models (every quantum possibility realises even at macroscopic level, but in different no-communicating universes)

-

- QM must be changed for macroscopic bodies: dynamical reduction models (where a non-linear modification of Schrödinger equation is introduced)

- We cannot have full oberver independent knowledge of reality: Qubism, Relational QM, …



- …

On the other hand, this problem simply would not exist in Hidden Variable Models since in this case the specification of the state by using state vectors is insufficient, there are further parameters (the hidden variables) that we ignore for characterizing the physical situation.

Spontaneous localization models

Ghirardi – Rimini- Weber

$$\Psi(x_1, ..., x_N) j(x - x_i)/R$$

$$j(x - x_i) = A \exp[-(x - x_i)^2/(2a)^2]$$

$$|R(x)|^2 = \int dx_1 ... dx_N |\Psi(x_1, ..., x_N) j(x - x_i)|^2$$

a ~ 10^{-7} m , rate ~ 10^{-17} s^{-1}

Interferometric Experiments

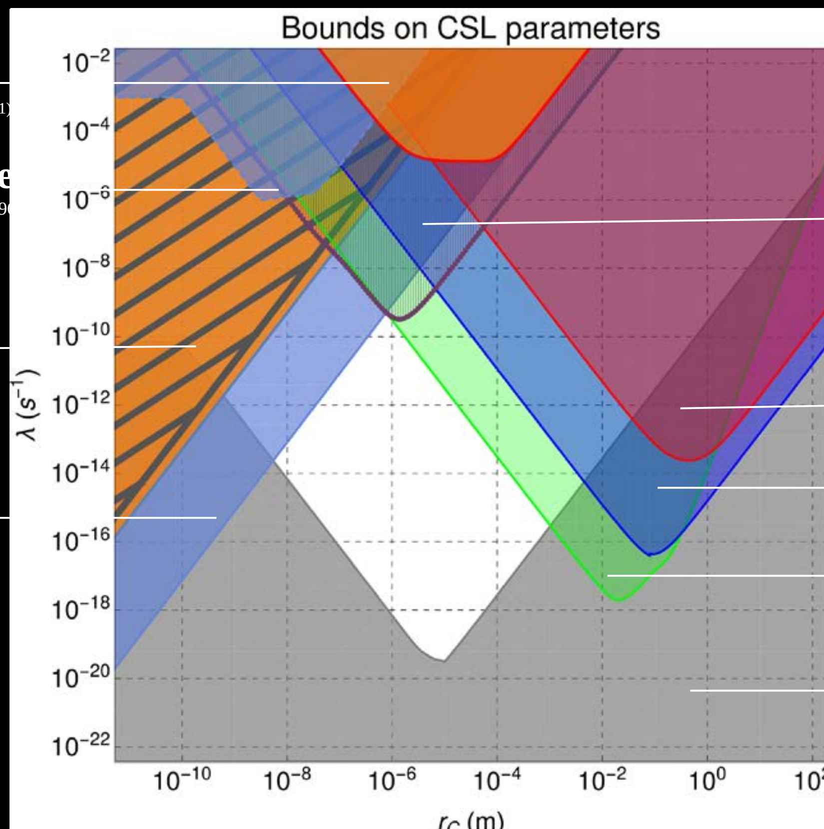
[from A.Bassi]

Diamonds
K. C. Lee *et al.*, Science. 334, 1253 (2011)
S. Belli *et al.*, PRA 94, 012108 (2016)

Macro-molecule
S. Eibenberger *et al.*, PCCP 15, 1469
(2013)
M. Toros *et al.*, ArXiv 1601.03672

Cold atom gas
F. Laloë *et al.* Phys. Rev. A 90, 052119 (2014)
T. Kovachy *et al.*, Phys. Rev. Lett. 114, 143004 (2015)
M. Bilardello *et al.*, Physica A 462, 764 (2016)

X-rays
C. Curceanu *et al.*, J. Adv. Phys. 4, 263 (2015).



Cantilever
A. Vinante *et al.*, Phys. Rev. Lett. 116, 090402 (2016)

Auriga
M. Carlesso *et al.* Phys. Rev. D 94, 124036 (2016)

LIGO
M. Carlesso *et al.* Phys. Rev. D 94, 124036 (2016)

LISA Pathfinder
M. Carlesso *et al.* Phys. Rev. D 94, 124036 (2016)

Theoretical
Collapse effective at the macroscopic level
Graphene disk: $N = 10^{11}$ amu, $d = 10^{-5}$ m, $T = 10^{-2}$ s

Is possible to build a Local Realistic Theory reproducing all the results of Standard Quantum Mechanics?

In the following years this question was considered solved by von Neumann theorem.

1952: Bohm describes a Hidden Variable Model

1964 Bell -> Bell Inequalities

These inequalities allow a test of **Local** HVT.

Non-local HVT are not concerned.

Example : the CH inequality

$$P(\theta_1,\theta_2)+P(\theta'_1,\theta'_2)+P(\theta'_1,\theta_2)-$$
$$-P(\theta_1,\theta'_2)-P(\theta'_1)-P(\theta_2)\leq 0$$

$P(\theta_i) =$ **Probability of finding a single particle in detector** i **with a certain property** θ_i **(e.g. spin/polarization direction with respect to a selected axis);**

$P(\theta_i,\theta_j) =$ **Joint probability of observing both one particle in** i **with a property** θ_i **and the other in** j θ_j

In a Local HVT:

$$P(\theta_i) = \int P(\theta_i, x)\rho(x)dx$$

$$P(\theta_i,\theta_j) = \int P(\theta_i,\theta_j, x)\rho(x)dx = \int P(\theta_i, x)\cdot P(\theta_j, x)\rho(x)dx$$

Consider 4 real variables $x, x', y, y' \in [0,1]$

$$xy + x'y' + x'y - xy' - x' - y \leq 0 \quad ??$$

$$x \geq x' \quad \Rightarrow \quad y(x-1) + x'(y-1) + y'(x'-x) \leq 0$$

$$x \leq x' \quad \Rightarrow \quad y(x'-1) + x'(y'-1) + x(y-y') \leq x'(y'-1) + x(y-1) \leq 0$$

$$\Downarrow$$

$P(\theta_i), P(\theta_i,\theta_j) \in [0,1] \quad \Rightarrow$ ***The CH inequality holds***

but

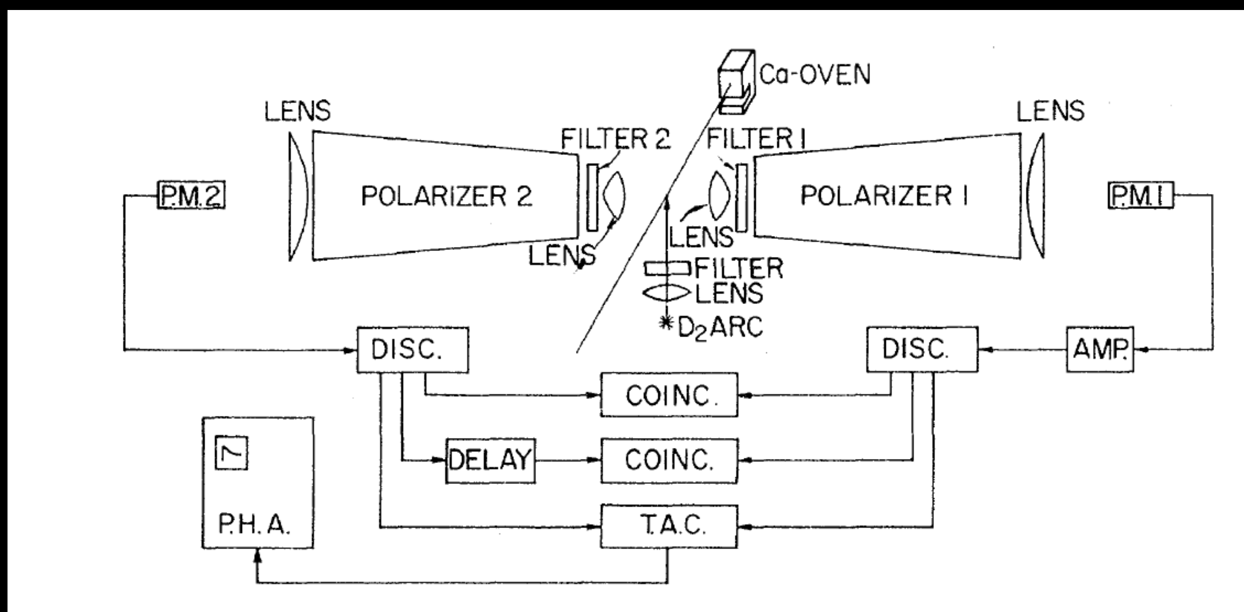
CH > 0 For certain values of parameters in SQM

Experimental Test of Local Hidden-Variable Theories*

Stuart J. Freedman and John F. Clauser

Department of Physics and Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

Phys. Rev. Lett. 28, 938 (1972)



In 70's experiments with **cascade atomic decay**

82 Orsay experiment *[A. Aspect et al., PRL. 49 (1982) 1804]*

Entangled photons from J=0 → J=1 → J=0 Calcium 40 decays

Addressed to detectors separated of 6 m

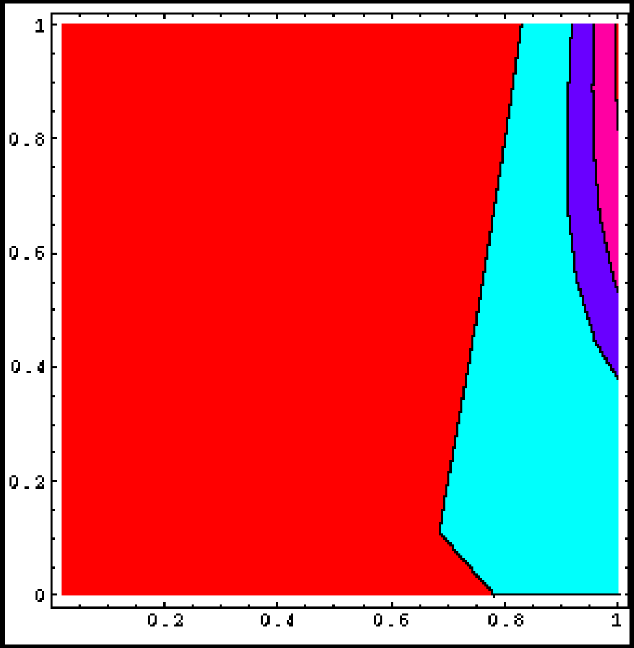
Space-like separation through acousto-optic switches

$$CH = 0.101 \pm 0.020$$

Very low detection efficiency

(e.g. 40 coincidences per second against typical production rate of 10^7 pairs per second)

CH/N



$$\frac{[(\,|H>|H> + f\,|V>|V>)\,]}{\sqrt{(1 + |f|^2)}}$$

Maximally entangled states require $\eta > 0.81$

Non-maximally entangled states allow to eliminate detection loophole with $\eta > 0.67$

Other systems?

i) Ions: Experiment with Berillum ions

High efficiency (98%), but subsystems are not separated during measurement *(Rowe et al., Nature 409 (01) 791)*

Improvement more recently: 1 m [Monroe et al., qph 0801.2184]

One needs many km (detection time around 50 μs)

ii) Neutrons *[Rauch]*

iii) Mesons (K,B) *[Foadi,Selleri PRA 61 (99) 012106-1,EPJ C14 (00) 469; Di Domenico NP B 450 (95) 293;Bramon,Garbarino, PRL 89 (02) 160401,Hiesmayr Fpl 14 (01)231]*

$$|\Psi\rangle = \frac{|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle}{\sqrt{2}} = \frac{|K_L\rangle|K_S\rangle - |K_S\rangle|K_L\rangle}{\sqrt{2}}$$

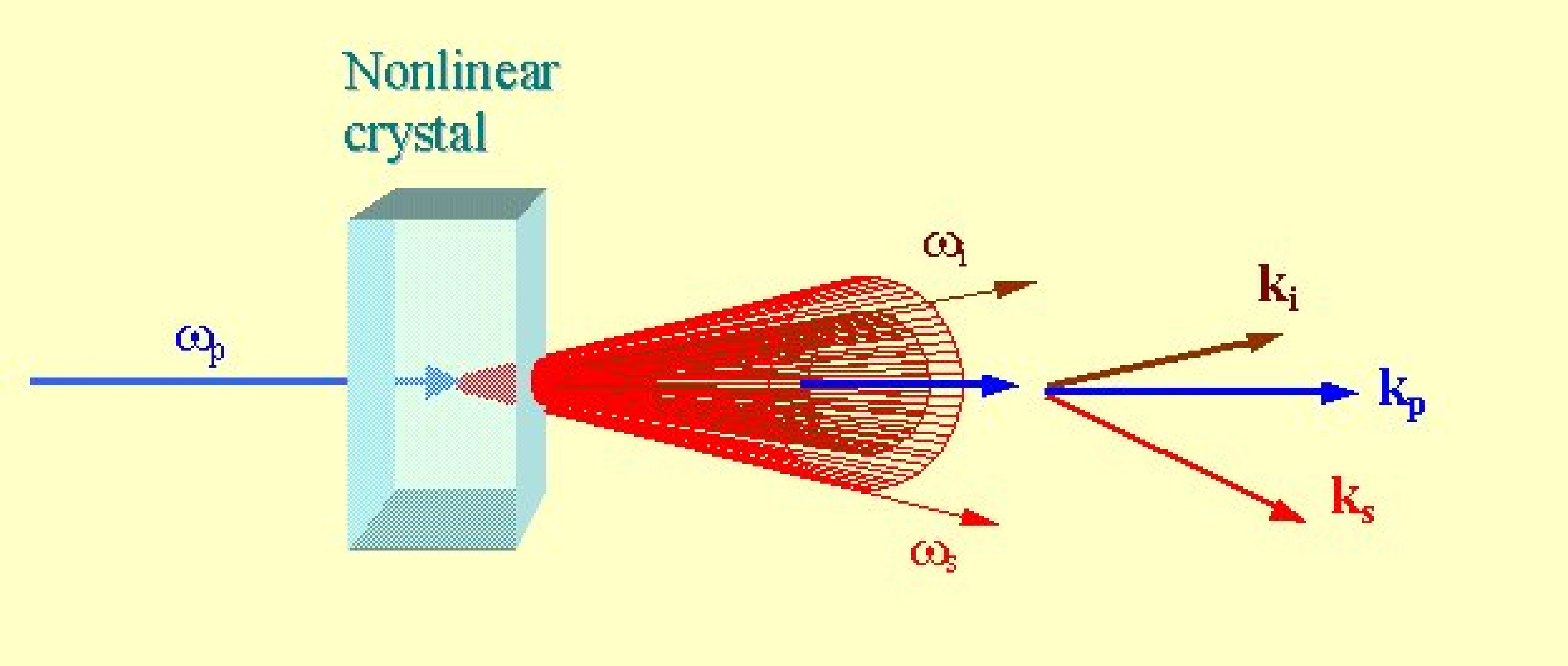
Some violation of Bell inequalities osserved by Belle [A.Go, JMO 51 (04) 991]

detection loophole reappears as HV can also determine

a) decay channel *[M.G. et al., PLB 513 (01) 401, FP 32 (02) 589]*

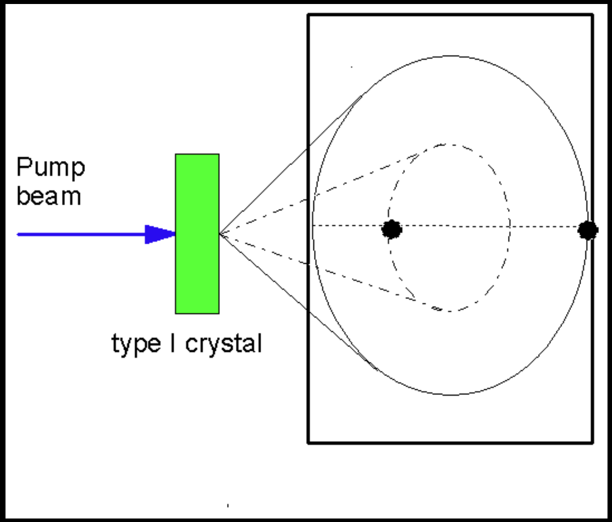
b) time of decay *[MG, PRA 69 (04) 022103]*

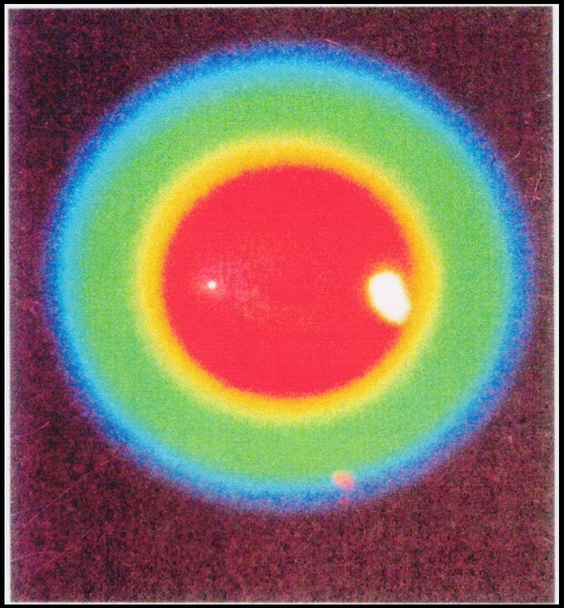
Parametric Down Conversion



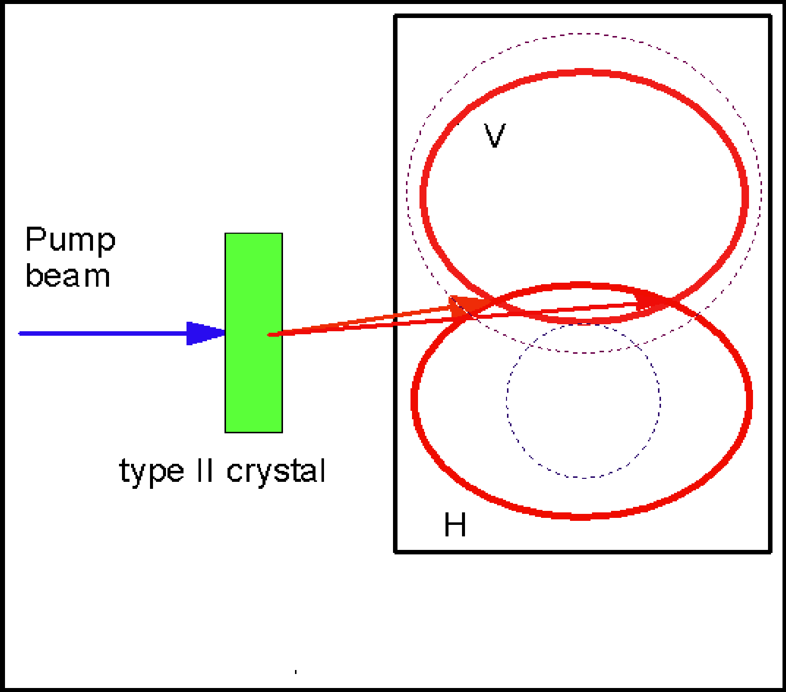
- Energy conservation: $\omega_p = \omega_s + \omega_i$
- Momentum conservation: $\vec{k}_p = \vec{k}_s + \vec{k}_i$
- ω_s and ω_i are emitted **at the same time**

type I PDC

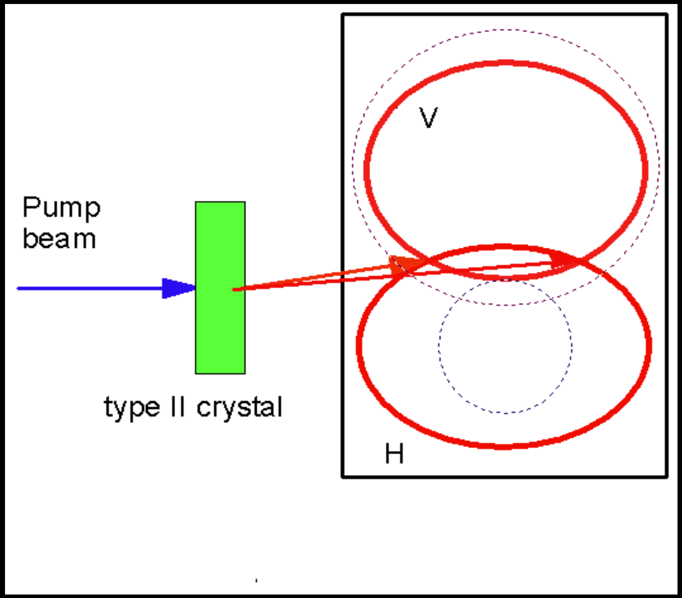




type II PDC



Brilliant sources:

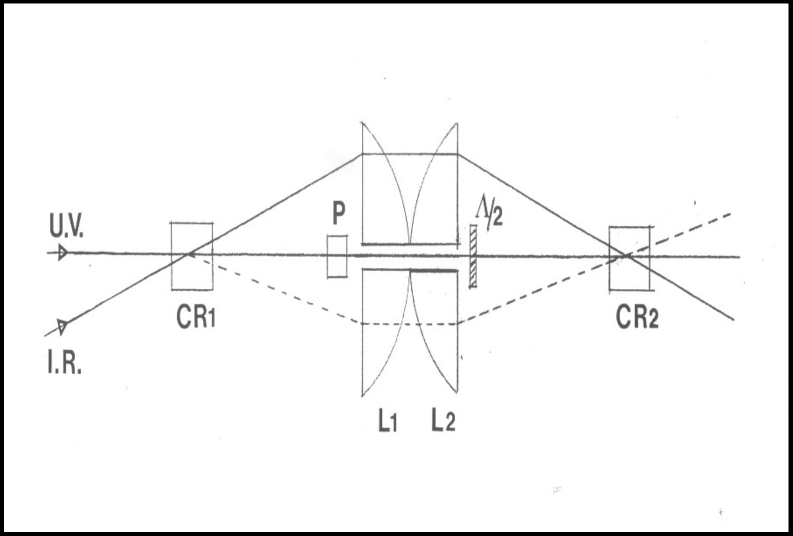


Type II PDC

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

Th: A. Garuccio
EXP: Zeilinger,
Sergienko, Kwiat et al.PRL 75 (95) 4337

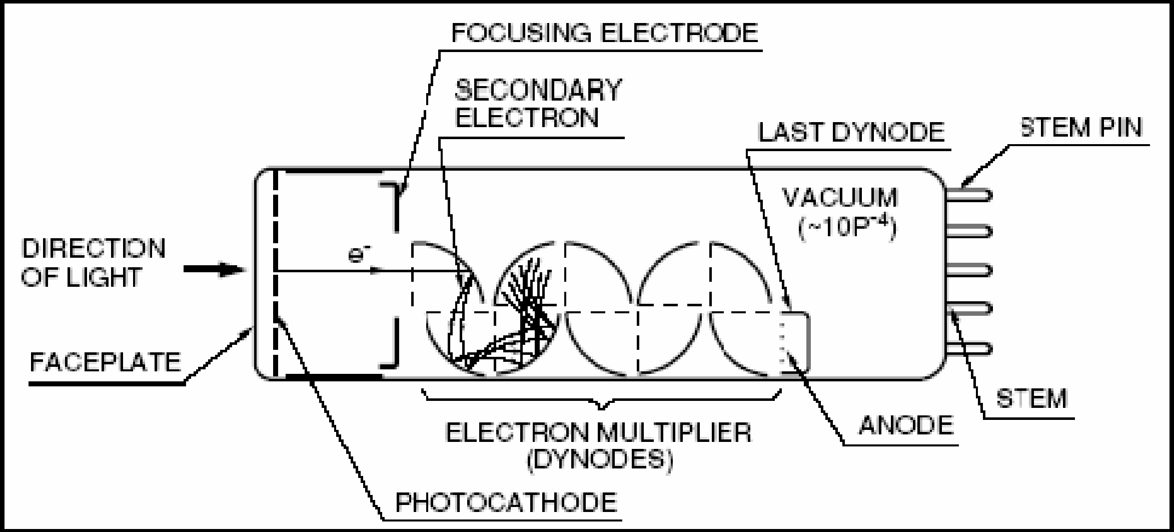
102 standard deviations violation of CHSH ineq. [P. Kwiat et al.,]

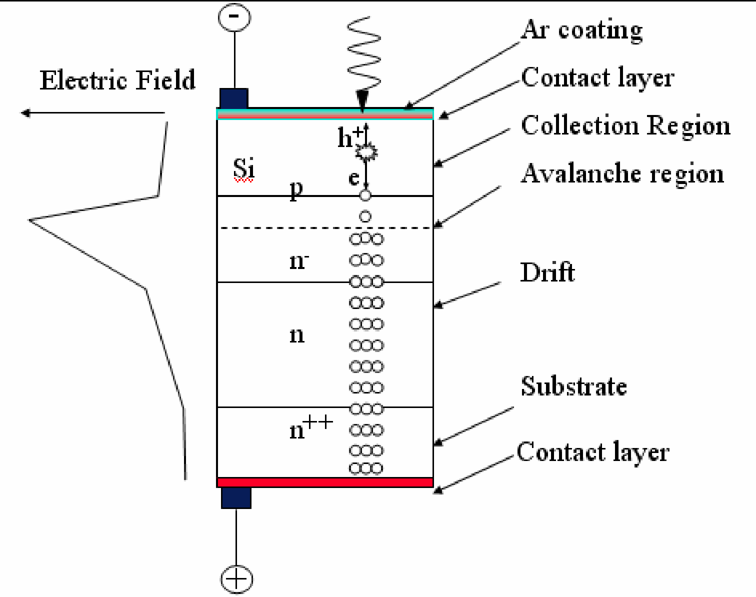


$$\frac{[(\,|H\rangle\,|H\rangle + f\,|V\rangle\,|V\rangle\,)]}{\sqrt{(1 + |f|^2)}}$$

Two type I PDC
Th: Hardy
Exp: P. Kwiat et al., PRL 83 (99) 3103
G. Brida, M.G., C. Novero and E. Predazzi, PLA 268 (2000) 12

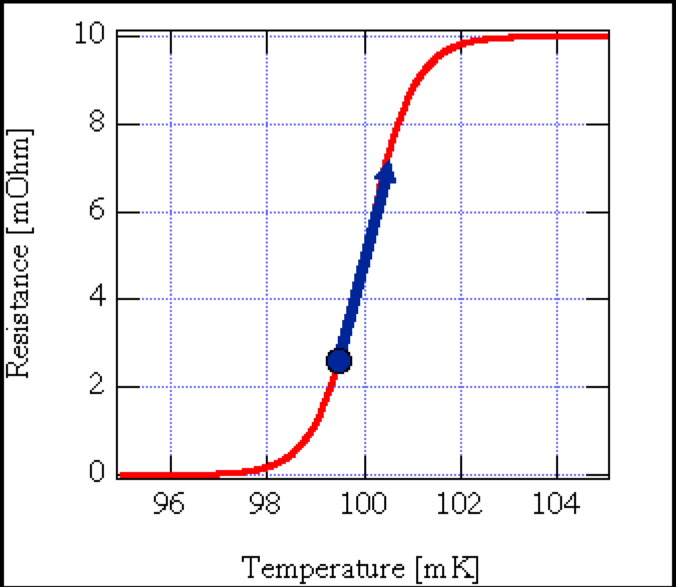
Photodetectors:detection loophole





TES

A transition-edge sensor is a thermometer made from a superconducting film operated near its transition temperature Tc.



Bell violation using entangled photons without the fair-sampling assumption

Marissa Giustina[1,2]*, Alexandra Mech[1,2]*, Sven Ramelow[1,2]*, Bernhard Wittmann[1,2]*, Johannes Kofler[1,3], Jörn Beyer[4], Adriana Lita[5], Brice Calkins[5], Thomas Gerrits[5], Sae Woo Nam[5], Rupert Ursin[1] & Anton Zeilinger[1,2]

PRL **111**, 130406 (2013) PHYSICAL REVIEW LETTERS week ending 27 SEPTEMBER 2013

Detection-Loophole-Free Test of Quantum Nonlocality, and Applications

B. G. Christensen,[1,*] K. T. McCusker,[1] J. B. Altepeter,[1] B. Calkins,[2] T. Gerrits,[2] A. E. Lita,[2] A. Miller,[2,3] L. K. Shalm,[2] Y. Zhang,[2,4] S. W. Nam,[2] N. Brunner,[5,6] C. C. W. Lim,[7] N. Gisin,[7] and P. G. Kwiat[1]

Experimental loophole-free violation of a Bell inequality using entangled electron spins separated by 1.3 km

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] M.W. Mitchell,[3,4] M. Markham,[5] D.J. Twitchen,[5] D. Elkouss,[1] S. Wehner,[1] T.H. Taminiau,[1,2] and R. Hanson[1,2,†]

- The two measurements must be set independently (locality loophole).
- The choice of the setting must be truly random (freedom-of-choice loophole)
- One should be able to detect all the pairs involved in the experiment or, at least, a sufficiently large fraction of them (detection loophole).

Furthermore:

- the number of emitted particle must be independent by measurement settings (production rate loophole)
- the presence of a coincidence window must not allow in a hidden variable scheme a situation where local setting may change the time at which the local event happens (coincidence loophole)
- an eventual memory of previous measurements must be considered in the statistical analysis since the data can be not-independent and identically distributed (memory loophole).

When all these conditions are satisfied, no room is left for local realistic hidden variable theories.

- the two measurements clearly space like separated (keeping in to account delays in transmission etc.) of setting choices and measurements is done. Thus, locality loophole is overcome
- the use of high detection efficiency TES together with non-maximally entangled states (as suggested by Eberhard) allowed a detection loophole free experiment.
- Independent random number generators based on laser phase diffusion guarantee the elimination of freedom-of-choice loophole (except ,as mentioned, in presence of superdetermininsm or other hypotheses that, by definition, do not allow a test through Bell inequalities).
- A perfect random choice of settings, as realized, does not permit production rate loophole.
- The use of a pulsed source eliminates coincidence loophole.
- An involved statistical analysis does not leave room for memory loophole.

Is the universe non-local and probabilistic?

-Non local HVT (de Broglie Bohm theory, Nelson stocastic model, …)

- Determinism at Planck scale [t' Hooft]

A physical system can evolve deterministically at Planck scale, but a probabilistic theory can derive at larger spatial scales due to loss of information (a quantum state is defined as a class of equivalence of states all having the same future).
Nowadays Bell inequalities do not involve the rigth degrees of freedom.

[Elze, Biro', Blasone et al., …]

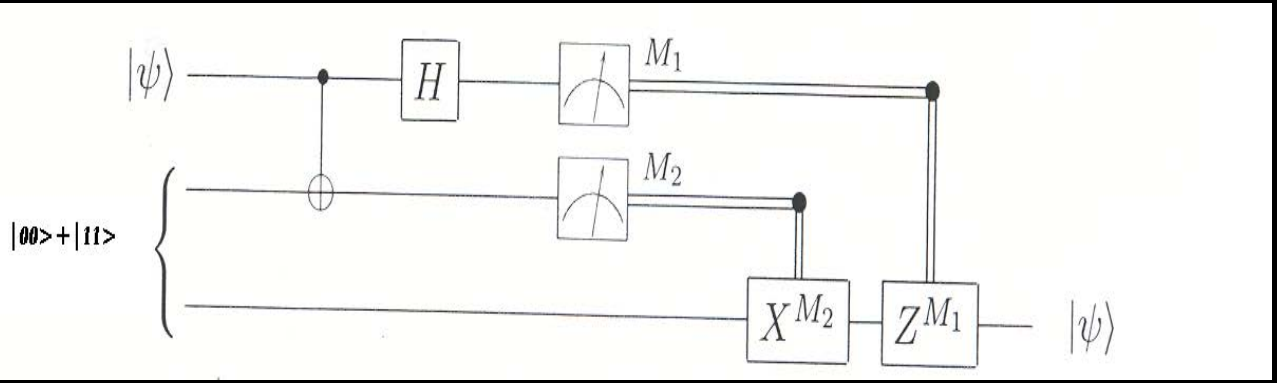
- Non-locality connected to compactified dimensions?
[Applied Science 9 (2019) 5406, arXiv 2211.02884]

- Teleportation

Teleportation is a protocol where an unknown state is measured in a

laboratory (Alice) together with a member of an entangled state; then, by applying a unitary operation on the other member of the entangled

state according to the result of this measurement (communicated by a classical channel) it is reconstructed in the second lab



a |0> + b |1> (|00> + |11>) ->

a|000 > + a |011> + b |110> + b |101> ->

½ (|00 > [a |0> + b |1>] +
|01> [a |1> + b |0>] +
|10> [a |0> - b |1>] +
|11> [a |1> - b |0>])

PHYSICAL REVIEW LETTERS

VOLUME 80 | 9 FEBRUARY 1998 | NUMBER 6

Experimental Realization of Teleporting an Unknown Pure Quantum State via Dual Classical and Einstein-Podolsky-Rosen Channels

D. Boschi,[1] S. Branca,[1] F. De Martini,[1] L. Hardy,[1,2] and S. Popescu[3,4]

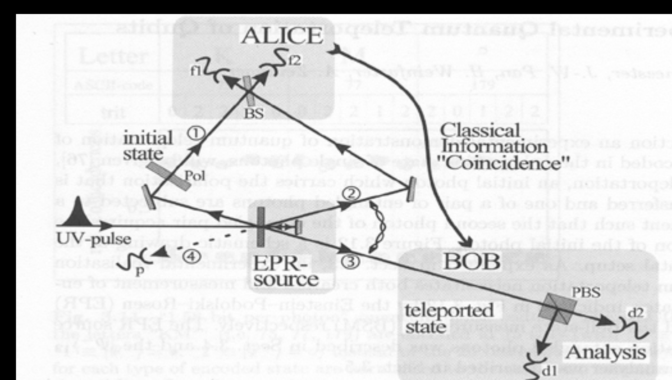
NATURE | VOL 390 | 11 DECEMBER 1997

Experimental quantum teleportation

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.



Quantum Technologies

QUANTUM INFORMATION (QUANTUM COMMUNICATION, QUANTUM COMPUTATION)

From bit (0,1), to quantum-bit (qubit) $|0\rangle$ $|1\rangle$

$$a\,|0\rangle + b\,|1\rangle$$

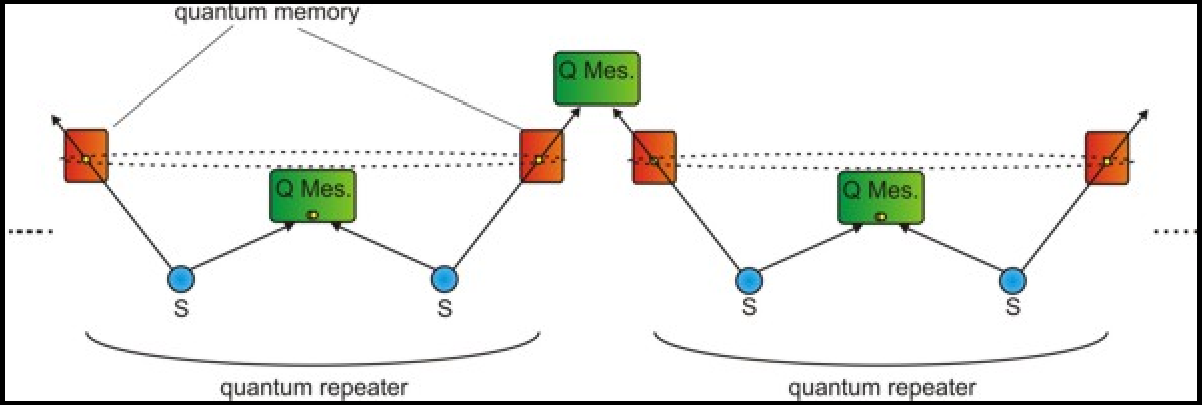
Many particles: entanglement

$$a_1\,|0\;0\;\ldots\;0\rangle + \ldots + a_N|1\;\ldots\;1\rangle$$

QUANTUM METROLOGY, IMAGING & SENSING ...

Quantum computation

Quantum Communication



QUANTUM METROLOGY, IMAGING & SENSING …