Title: From Einstein's Intuition to Quantum Bits

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Abstract: Many experts are convinced that large scale, practical implementations of quantum information systems hold great promise for society, much as the laser and the transistor have already revolutionized the world. This stems from a long history of research that included an intense, raging battle of epic proportions between scientific giants. In tracing these steps, you will learn why Albert Einstein and Niels Bohr argued over the nature of entangled states where pairs of sub-atomic particles are strangely correlated from 1935 until their very deaths. You will also find out how, decades later, John Bell discovered his famous inequalities that made it possible for experimentalists, including Alain Aspect and others, to settle the great debate and help propel a new era of fundamental understanding with concepts and methods that seek to harness unique properties of atoms to process and transmit information.

INSTITUT d'OPTIQUE GRADUATE SCHOOL

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

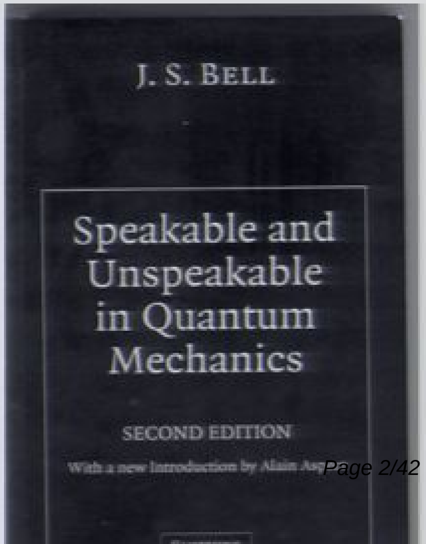
From Einstein's intuition to quantum bits: a new quantum age?

Alain ASPECT - Institut d'Optique - Palaiseau

Waterloo, September 3, 2007

To know more:

- AA: "Bell's theorem: the naïve view of an experimentalist" arXiv: quant-ph/0402001
- AA: "John Bell and the second quantum revolution" in "Speakable and Unspeakable in Quantum Mechanics" (Cambridge University Press 2004).



Einstein and quantum physics

A founding contribution (1905)

Light is made of quanta, later named photons, which have well defined energy and momentum. Nobel 1922.

A fruitful objection (1935): entanglement

Einstein, Podolsky, Rosen (EPR): The quantum formalism allows for amazing situations (pairs of entangled particles): the formalism must be completed.

Objection underestimated for a long time (except Bohr's answer, 1935) until Bell's theorem (1964) and the acknowledgement of its importance (1970-80).

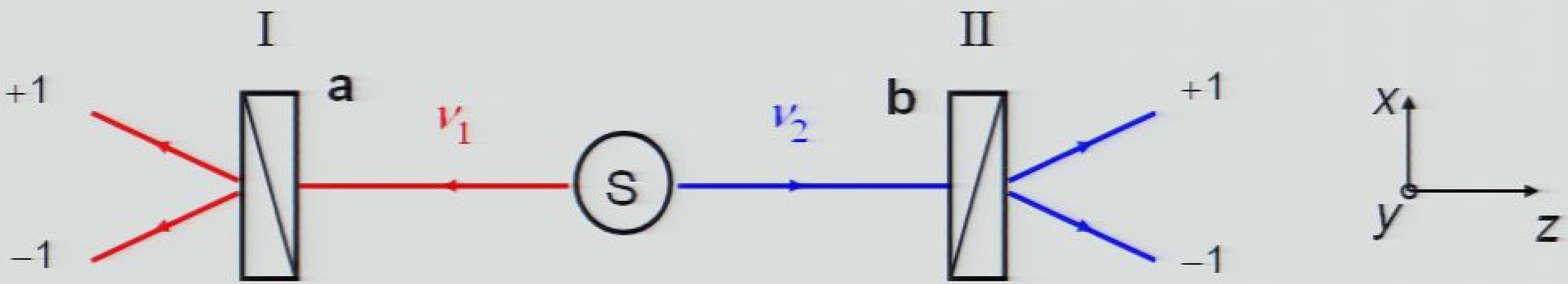
Entanglement has open the way to quantum information (198x-20??)

Is it possible (necessary) to explain the probabilistic character of quantum predictions by invoking a supplementary underlying level of description (supplementary parameters, hidden variables) ?

It was the conclusion of the Einstein-Podolsky-Rosen reasoning (1935). Bohr strongly opposed this conclusion.

Bell's theorem (1964) has allowed us to settle the debate.

The EPR GedankenExperiment with photons correlated in polarization

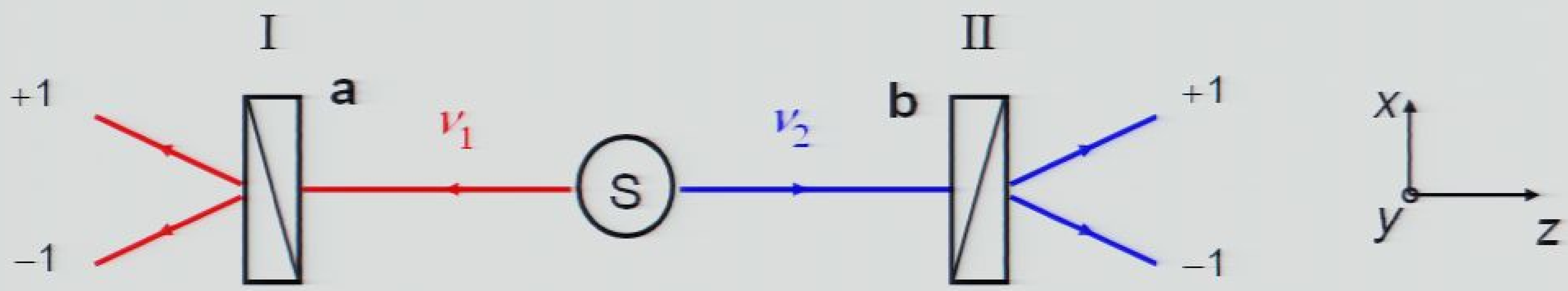


Measurement of the polarization of ν_1 along orientation **a** and and of polarization of ν_2 along orientation **b** : results +1 or −1

⇒ Probabilities to find +1 ou −1 for ν_1 (measured along **a**) and +1 or −1 for ν_2 (measured along **b**).

Single probabilities	Joint probabilities
$P_+(\mathbf{a})$, $P_-(\mathbf{a})$	$P_{++}(\mathbf{a},\mathbf{b})$, $P_{+-}(\mathbf{a},\mathbf{b})$
$P_+(\mathbf{b})$, $P_-(\mathbf{b})$	$P_{-+}(\mathbf{a},\mathbf{b})$, $P_{--}(\mathbf{a},\mathbf{b})$

The EPR GedankenExperiment with photons correlated in polarization



For the entangled EPR state… $|\Psi(\nu_1,\nu_2)\rangle = \frac{1}{\sqrt{2}}\{|x,x\rangle + |y,y\rangle\}$

Quantum mechanics predicts results separately random … $P_+(\mathbf{a}) = P_-(\mathbf{a}) = \frac{1}{2}\ ;\ P_+(\mathbf{b}) = P_-(\mathbf{b}) = \frac{1}{2}$

but strongly correlated:

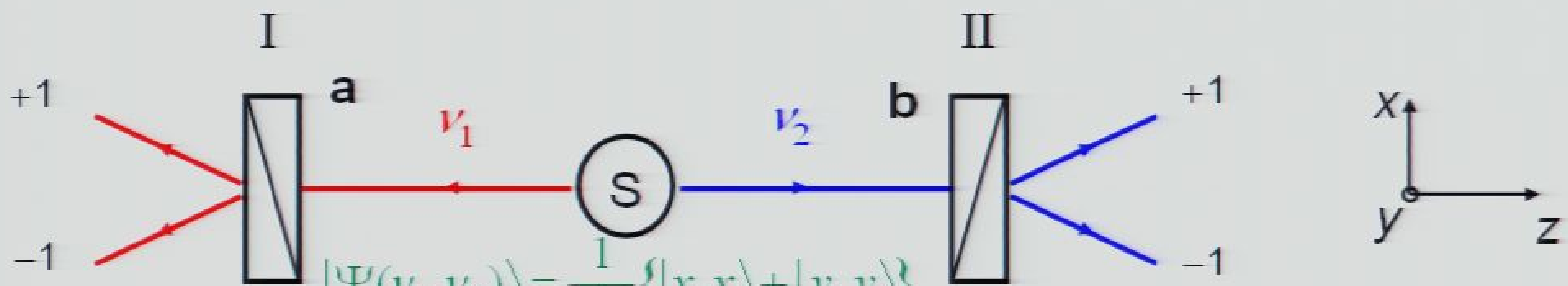
$$P_{++}(\mathbf{a},\mathbf{b}) = P_{--}(\mathbf{a},\mathbf{b}) = \frac{1}{2}\cos^2(\mathbf{a},\mathbf{b})$$

$$P_{+-}(\mathbf{a},\mathbf{b}) = P_{-+}(\mathbf{a},\mathbf{b}) = \frac{1}{2}\sin^2(\mathbf{a},\mathbf{b})$$

$$P_{++}(0) = P_{--}(0) = \frac{1}{2}$$

$$P_{+-}(0) = P_{-+}(0) = 0$$

Coefficient of correlation of polarization (EPR state)



$$|\Psi(\nu_1,\nu_2)\rangle = \frac{1}{\sqrt{2}}\{|x,x\rangle + |y,y\rangle\}$$

Quantitative expression of the correlations between results of measurements in I et II: coefficient:

$$E = P_{++} + P_{--} - P_{+-} - P_{-+} = P(\text{résutats id°}) - P(\text{résutats } \neq)$$

QM predicts, for parallel polarizers (a,b) = 0

$$P_{++} = P_{--} = \frac{1}{2} \quad \Rightarrow \quad E_{MQ} = 1$$

$$P_{+-} = P_{-+} = 0$$

Total correlation

More generally, for an arbitrary angle (a,b) between polarizers

$$E_{MQ}(\mathbf{a},\mathbf{b}) = \cos 2(\mathbf{a},\mathbf{b})$$

How to "understand" the EPR correlations predicted by quantum mechanics?

Can we derive an image from the QM calculation?

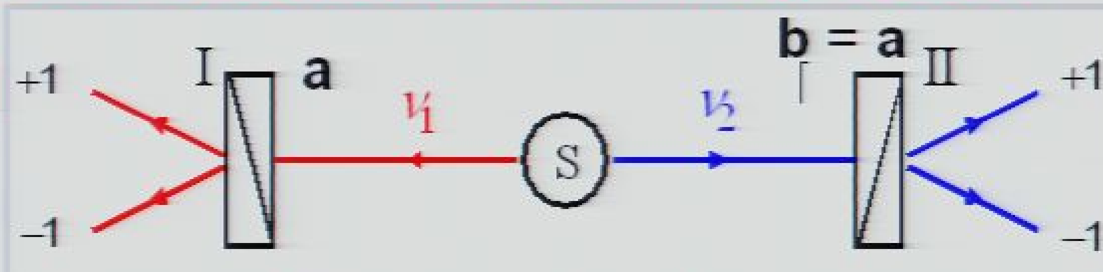
The direct calculation $P_{++}(\mathbf{a},\mathbf{b}) = \left|\langle +_{\mathbf{a}}, +_{\mathbf{b}} | \Psi(\nu_1,\nu_2)\rangle\right|^2 = \frac{1}{2}\cos^2(\mathbf{a},\mathbf{b})$ is done in an abstract space, configuration space, where the two particles are described globally: impossible to extract an image in real space where the two photons are separated.

Related to the non factorability of the entangled state:

$$|\Psi(\nu_1,\nu_2)\rangle = \frac{1}{\sqrt{2}}\{|x,x\rangle + |y,y\rangle\} \neq |\phi(\nu_1)\rangle \cdot |\chi(\nu_2)\rangle$$

One cannot identify properties attached to each photon separately

An image of the EPR correlations derived from a quantum calculation



$$|\Psi(\nu_1,\nu_2)\rangle = \frac{1}{\sqrt{2}}\{|x,x\rangle + |y,y\rangle\} = \frac{1}{\sqrt{2}}\{|+_{\mathbf{a}},+_{\mathbf{a}}\rangle + |-_{\mathbf{a}},-_{\mathbf{a}}\rangle\}$$

2 step calculation (standard QM)

1) Measure on ν_1 by I (along **a**)

$\Rightarrow$ result $+1$ $|+_{\mathbf{a}}\rangle$

or

$\Rightarrow$ result -1 $|-_{\mathbf{a}}\rangle$

Just after the measure, "collapse of the state vector": projection onto the eigenspace associated to the result

$|+_{\mathbf{a}},+_{\mathbf{a}}\rangle$

or

$|-_{\mathbf{a}},-_{\mathbf{a}}\rangle$

2) Measure on ν_2 by II (along $\mathbf{b} = \mathbf{a}$)

- If one has found $+1$ for ν_1 then the state of ν_2 is $|+_{\mathbf{a}}\rangle$ and the measurement along $\mathbf{b} = \mathbf{a}$ yields $+1$;
- If one has found -1 for ν_1 then the state of ν_2 is $|-_{\mathbf{a}}\rangle$ and the measurement along $\mathbf{b} = \mathbf{a}$ yields -1;

The measurement on ν_1 seems to influence instantaneously at a distance the state of ν_2 : unacceptable for Einstein (relativistic causality)

A classical image for the correlations at a distance (suggested by the EPR reasoning)

- The two photons of the same pair bear from their very emission an identical property (λ), that will determine the results of polarization measurements.
- The property λ differs from one pair to another.

exemple

$\lambda = +_a$

ou

$\lambda = -_a$

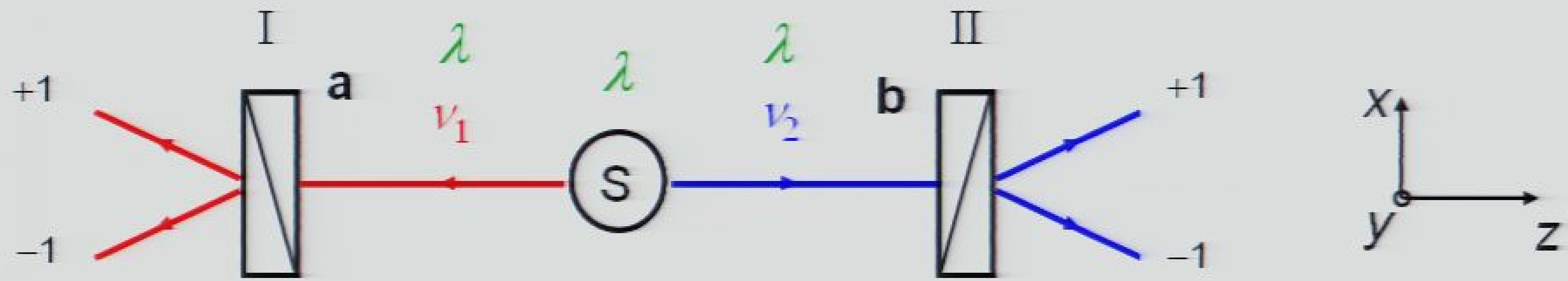


Image simple and convincing (analogue of identical chromosomes for twin brothers), but… …amounts to completing quantum formalism: λ = supplementary parameter, "hidden variable".

⇨ Bohr disagreed: QM description is complete, you cannot add anything to it

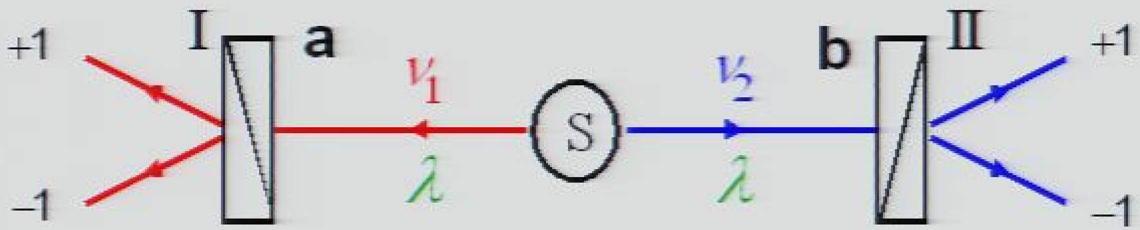
A debate for many decades

Intense debate between Bohr and Einstein…

… without much attention from a majority of physicists

- Quantum mechanics accumulates success:
  - Understanding nature: structure and properties of matter, light, and their interaction (atoms, molecules, absorption, spontaneous emission, solid properties, superconductivity, superfluidity, elementary particles …)
  - New concepts leading to revolutionary inventions: transistor, laser…
- No disagreement on the validity of quantum predictions, only on its interpretation.

1964: Bell's formalism



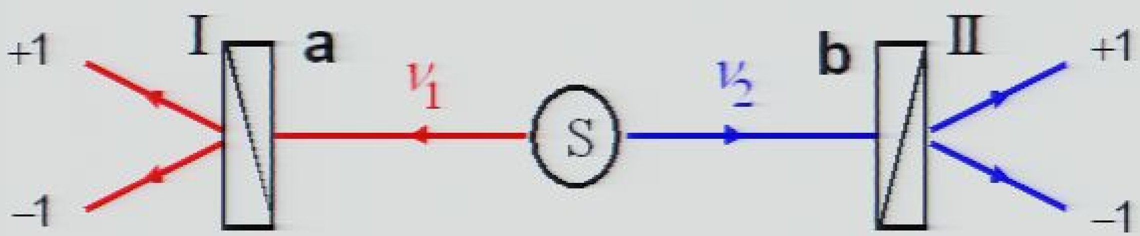
Consider local supplementary parameters theories (in the spirit of Einstein's ideas on EPR correlations):

- The two photons of a same pair have a common property λ (sup. param.) determined at the joint emission

- The supplementary parameter λ determines the results of measurements at I and II $\Leftrightarrow$ $A(\lambda, \mathbf{a}) = +1 \text{ or } -1$ at polarizer I; $B(\lambda, \mathbf{b}) = +1 \text{ or } -1$ at polarizer II

- The supplementary parameter λ is randomly distributed among pairs $\Leftrightarrow$ $\rho(\lambda) \geq 0$ and $\int \rho(\lambda) d\lambda = 1$ at source S

1964: Bell's theorem

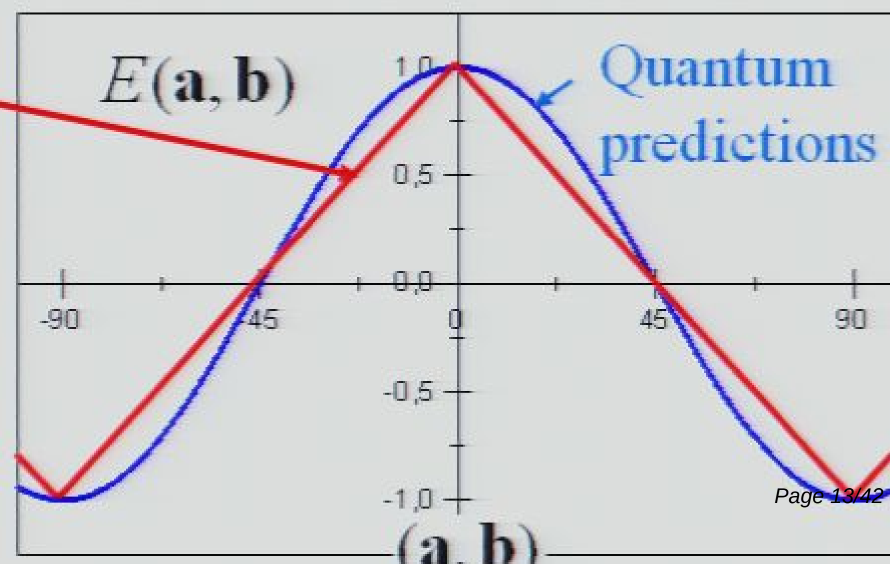


No local hidden variable theory (in the spirit of Einstein's ideas) can reproduce quantum mechanical predictions for EPR correlations for all the orientations of polarizers.

Example of LHVT

- Common direction of polarisation λ, different for each pair $\rho(\lambda) = 1/2\pi$
- Result (±1) depends on the angle between λ and polarizer orientation (**a** or **b**) $A(\lambda, \mathbf{a}) = \text{sign}\{\cos 2(\theta_{\mathbf{a}} - \lambda)\}$

  $B(\lambda, \mathbf{b}) = \text{sign}\{\cos 2(\theta_{\mathbf{b}} - \lambda)\}$



Not bad, but no exact agreement

Impossible to have an agreement at *all* orientations, whatever the model

Any local hidden variables theory $\Rightarrow$ Bell's inequalities

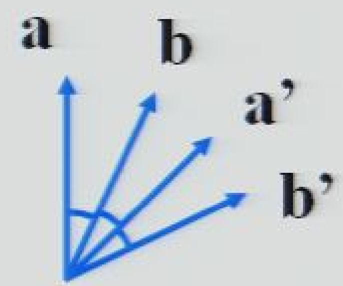
$-2 \leq S \leq 2$ avec $S = E(\mathbf{a},\mathbf{b}) - E(\mathbf{a},\mathbf{b}') + E(\mathbf{a}',\mathbf{b}) + E(\mathbf{a}',\mathbf{b}')$

CHSH inequ. (Clauser, Horne, Shimony, Holt, 1969)

Quantum mechanics $E_{\mathrm{MQ}}(\mathbf{a},\mathbf{b}) = \cos 2(\mathbf{a},\mathbf{b})$

For orientations $(\mathbf{a},\mathbf{b}) = (\mathbf{b},\mathbf{a}') = (\mathbf{a}',\mathbf{b}) = \dfrac{\pi}{8}$

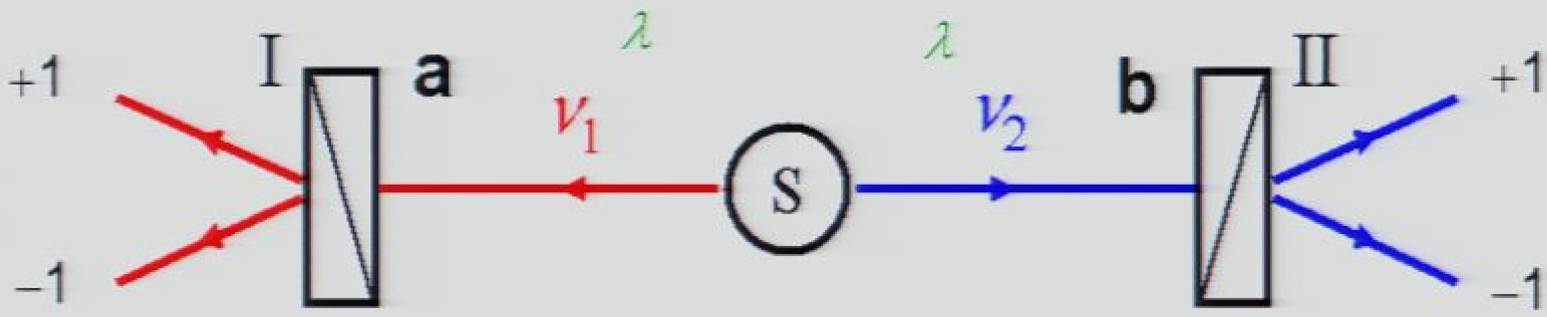
$S_{\mathrm{QM}} = 2\sqrt{2} = 2.828\ldots > 2$



CONFLICT ! The possibility to complete quantum mechanics is no longer a matter of taste (of interpretation). It has turned into an experimental question.

Conditions for a conflict with QM

($\Rightarrow$ hypotheses for Bell's inequalities)



Supplementary parameters λ carried along by each particle.
Explanation of correlations « à la Einstein » attributing individual properties to each separated particle: local realist world view.

Bell's locality condition

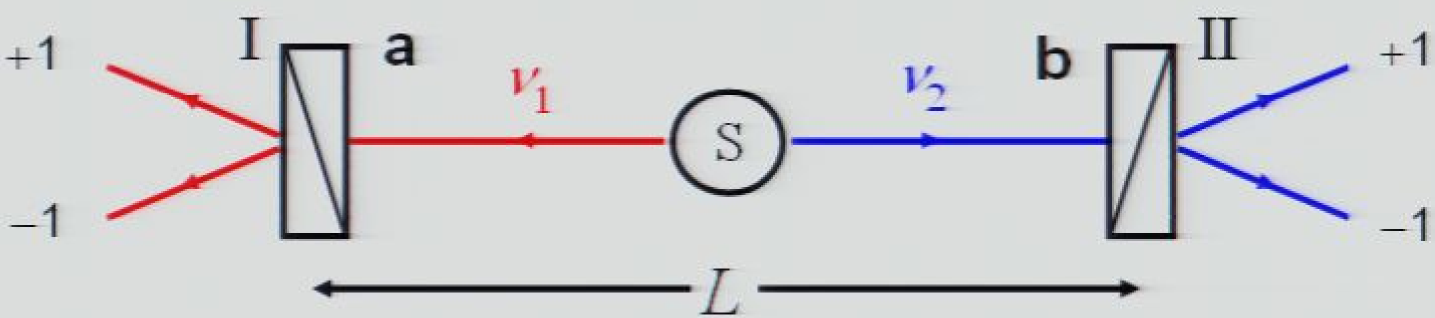
- The result $A(\lambda, \mathbf{a})$ of the measurement on ν_1 by I does not depend on the orientation **b** of distant polarizer II (and conv.)
- The distribution $\rho(\lambda)$ of supplementary parameters over the pairs does not depend on the orientations **a** and **b**.

Bell's locality condition

$A(\lambda, \mathbf{a}, \not{\mathbf{b}}) \qquad B(\lambda, \not{\mathbf{a}}, \mathbf{b}) \qquad \rho(\lambda, \not{\mathbf{a}}, \not{\mathbf{b}})$

can be stated as a reasonable hypothesis, but…

…in an experiment with variable polarizers (orientations modified faster than the propagation time L/c of light between polarizers) Bell's locality condition becomes a consequence of Einstein's relativistic causality (no faster than light influence)



Conflict between quantum mechanics and Einstein's world view (local realism based on relativity).

From epistemology debates to experimental tests

Bell's theorem demonstrates a quantitative incompatibility between the local realist world view (à la Einstein) which is constrained by Bell's inequalities and quantum predictions for pairs of entangled particles which violate Bell's inequalities.

An experimental test is possible.

When Bell's paper was written (1964), there was no experimental result available to be tested against Bell's inequalities:

- Bell's inequalities apply to all correlations that can be described within classical physics (mechanics, electrodynamics).
- B I apply to most of the situations which are described within quantum physics (except EPR correlations)

One must carry out specifically designed experiments

Three generations of experiments

Pioneers (1972-76): Berkeley, Harvard, Texas A&M

- First results contradictory (Clauser = QM; Pipkin ≠ QM), but clear trend in favour of Quantum mechanics (Clauser, Fry)
- Significantly different from the ideal scheme

Institut d'optique experiments (1975-82)

- A source of entangled photons of unprecedented efficiency
- Schemes closer and closer to the ideal GedankenExperiment
- Test of quantum non locality (relativistic separation)

Third generation experiments (1988-): Maryland, Rochester, Malvern, Genève, Innsbruck, Los Alamos, Paris, Boulder, Urbana Champaign

- New sources of entangled pairs
- Closure of the last loopholes
- Entanglement at very large distance
- Entanglement on demand

Orsay's source of pairs of entangled photons (1981)

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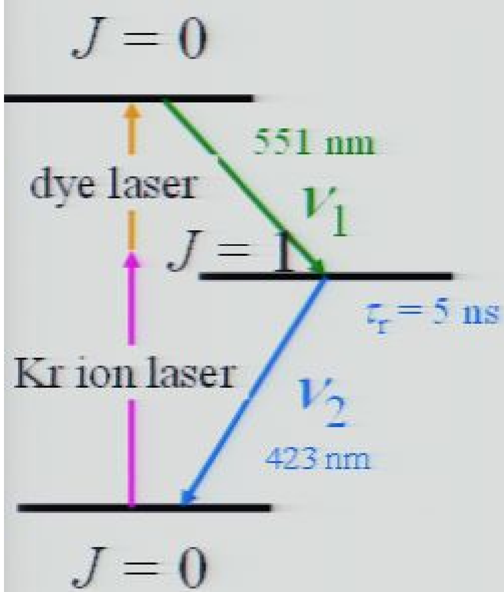

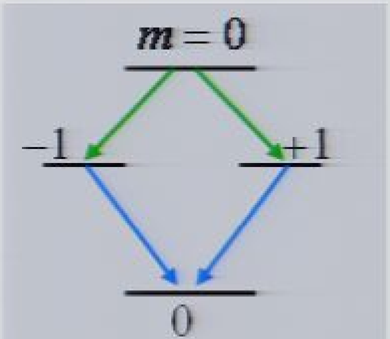

$$\frac{1}{\sqrt{2}}\left\{\left|\sigma_+,\sigma_-\right\rangle + \left|\sigma_-,\sigma_+\right\rangle\right\}$$

$$= \frac{1}{\sqrt{2}}\left\{\left|x,x\right\rangle + \left|y,y\right\rangle\right\}$$

Two photon selective excitation

☺ 100 coincidences per second

1% precision for 100 s counting

Orsay's source of pairs of entangled photons (1981)

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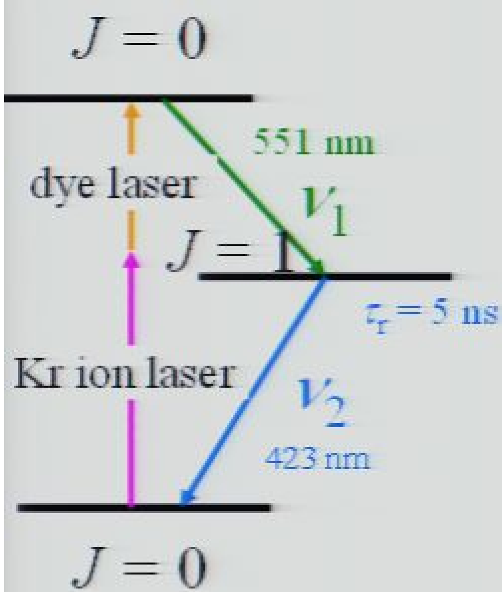

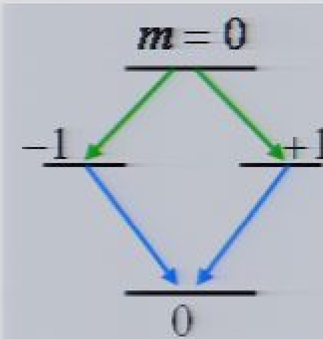

$$\frac{1}{\sqrt{2}}\left\{\left|\sigma_+,\sigma_-\right\rangle+\left|\sigma_-,\sigma_+\right\rangle\right\}$$

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Two photon selective excitation

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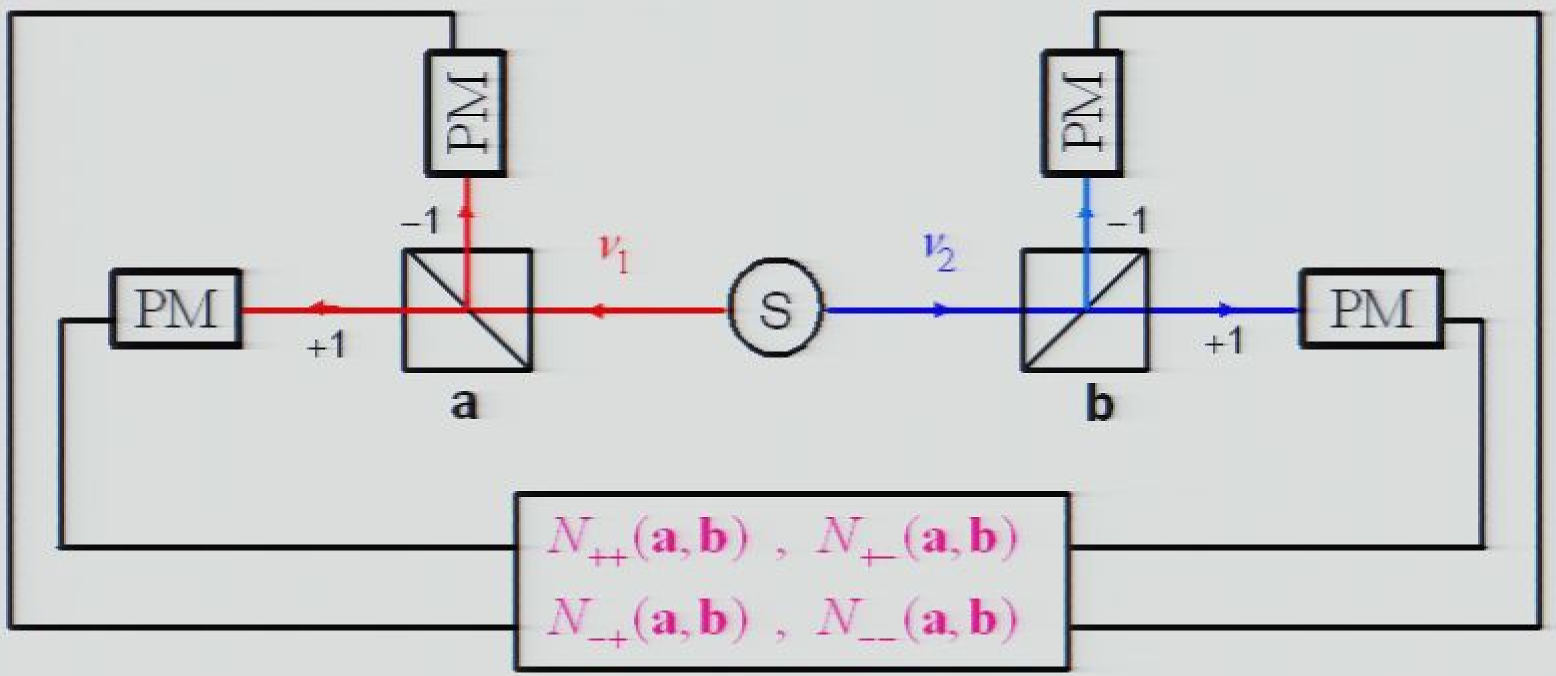
Polarizers at 6 m from the source:

violation of Bell's inequalities,

entanglement survives at large distance

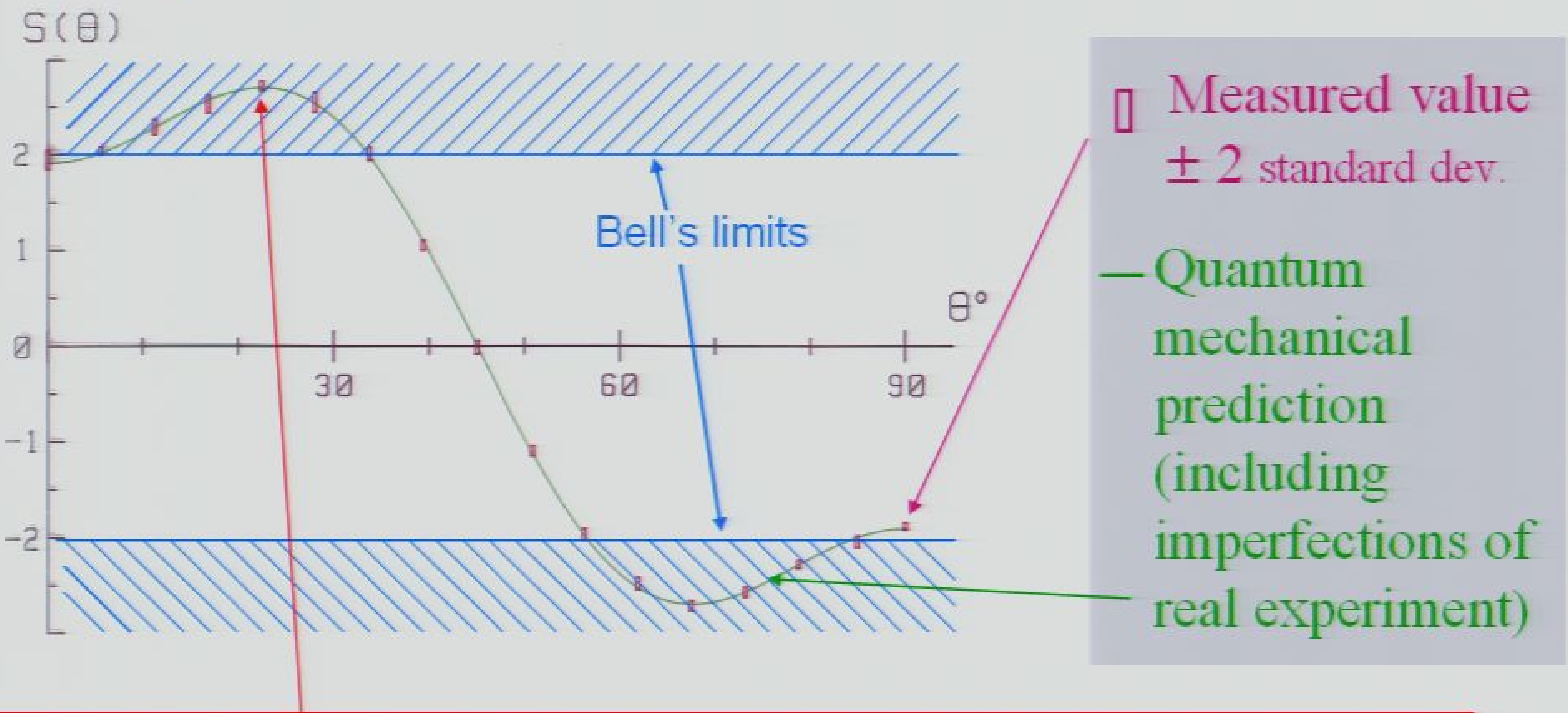
Experiment with 2-channel polarizers (AA, P. Grangier, G. Roger, 1982)



Direct measurement of the polarization correlation coefficient:
simultaneous measurement of the 4 coincidence rates

$$E(\mathbf{a},\mathbf{b}) = \frac{N_{++}(\mathbf{a},\mathbf{b}) - N_{+-}(\mathbf{a},\mathbf{b}) - N_{-+}(\mathbf{a},\mathbf{b}) + N_{--}(\mathbf{a},\mathbf{b})}{N_{++}(\mathbf{a},\mathbf{b}) + N_{+-}(\mathbf{a},\mathbf{b}) + N_{-+}(\mathbf{a},\mathbf{b}) + N_{--}(\mathbf{a},\mathbf{b})}$$

Experiment with 2-channel polarizers (AA, P. Grangier, G. Roger, 1982)



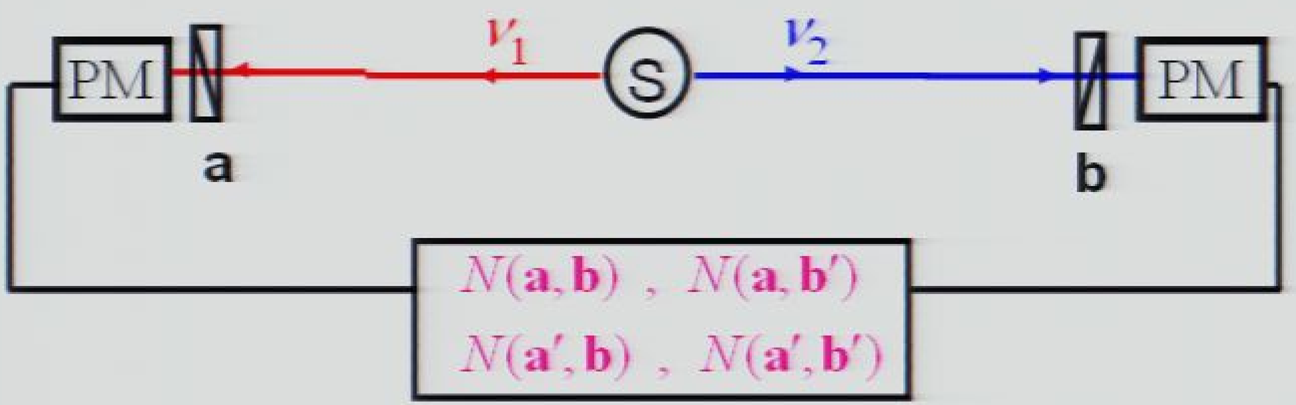
For $\theta = (\mathbf{a}, \mathbf{b}) = (\mathbf{b}, \mathbf{a}') = (\mathbf{a}', \mathbf{b}) = 22.5°$ $\quad S_{\text{exp}}(\theta) = 2.697 \pm 0.015$

Violation of Bell's inequalities $S \leq 2$ by more than $40\ \sigma$

Excellent agreement with quantum predictions $S_{\text{MQ}} = 2.70$

Experiment with variable polarizers AA, J. Dalibard, G. Roger, PRL 1982

Impose locality as a consequence of relativistic causality: change of polarizer orientations faster than the time of propagation of light between the two polarizers (40 nanoseconds for $L = 12$ m)



Experiment with variable polarizers

AA, J. Dalibard, G. Roger, PRL 1982

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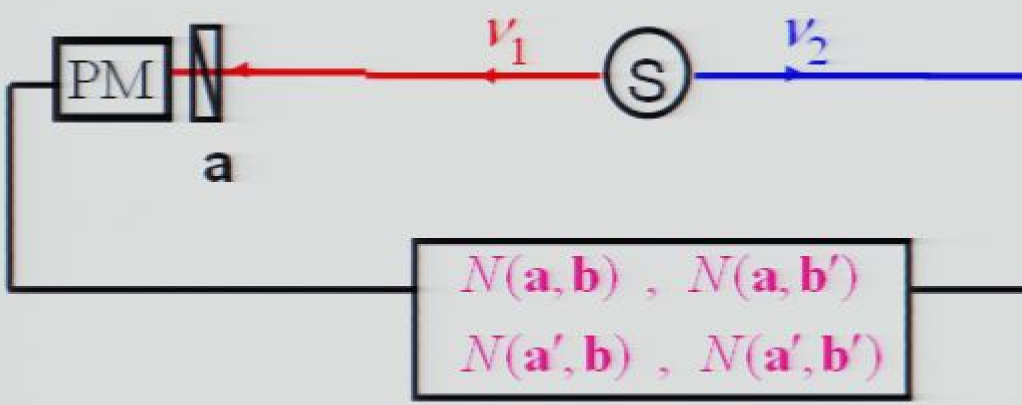
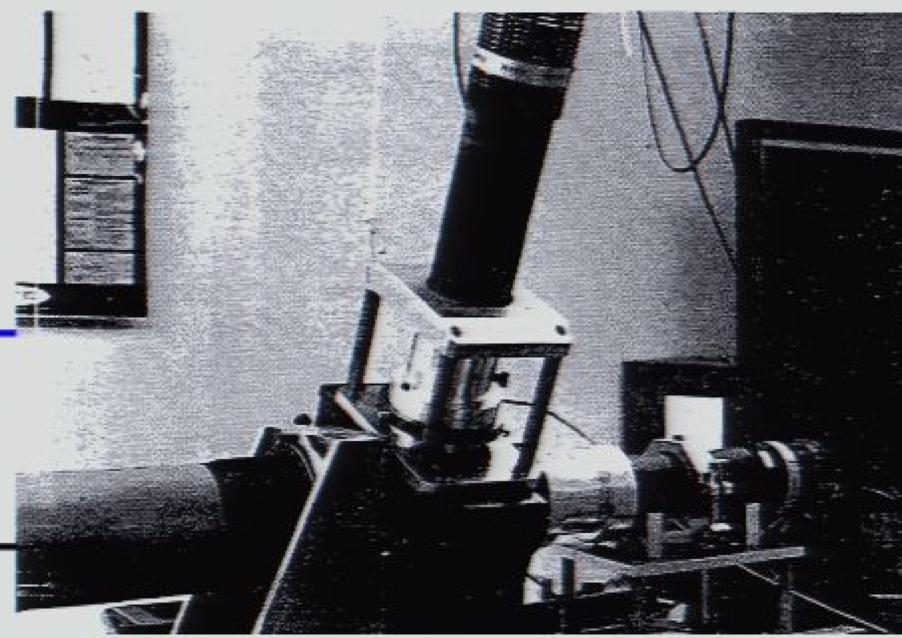
☹ Not realist with massive polarizer





Experiment with variable polarizers AA, J. Dalibard, C

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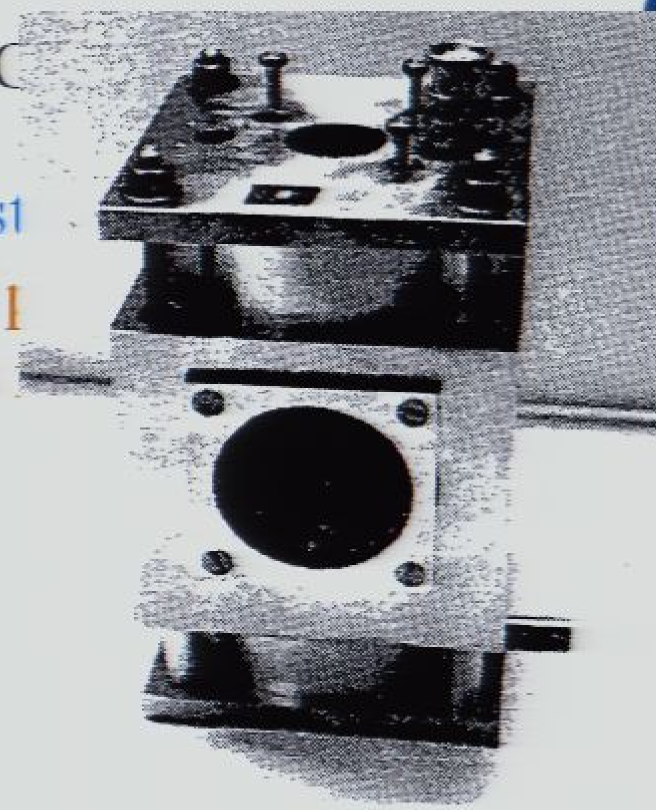
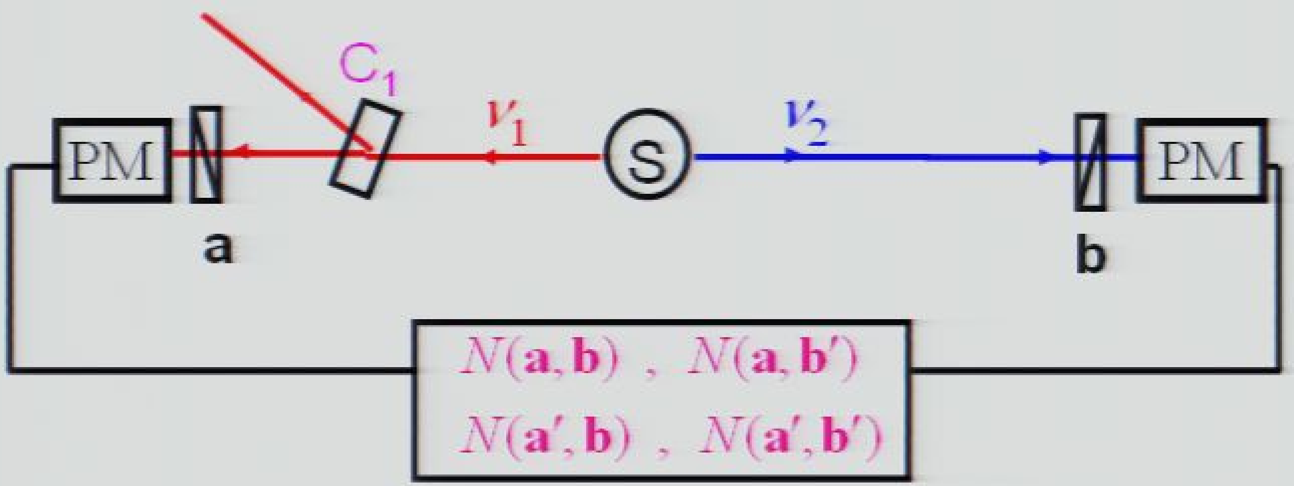
Impose locality as a consequence of relativist polarizer orientations faster than the time of between the two polarizers (40 nanoseconds

☹ Not realist with massive polarizer

☺ Possible with optical switch





Between two switching: 10 ns $< L/c \approx 40$ ns

Experiment with variable polarizers AA, J. Dalibard, G. Roger, PRL 1982

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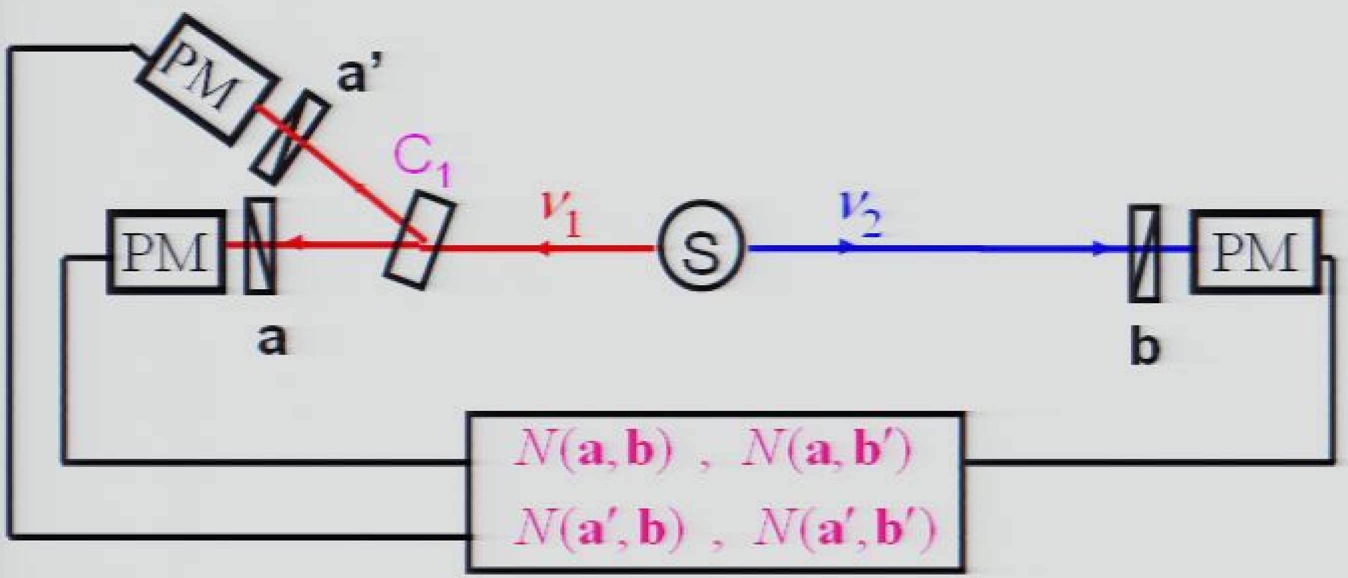

Switch C_1 redirects light
- either towards pol. in orient. **a**
- or towards pol. in orient. **a'**

Equivalent to a single polarizer switching between **a** and **a'**

Between two switching: 10 ns $< L/c \approx 40$ ns

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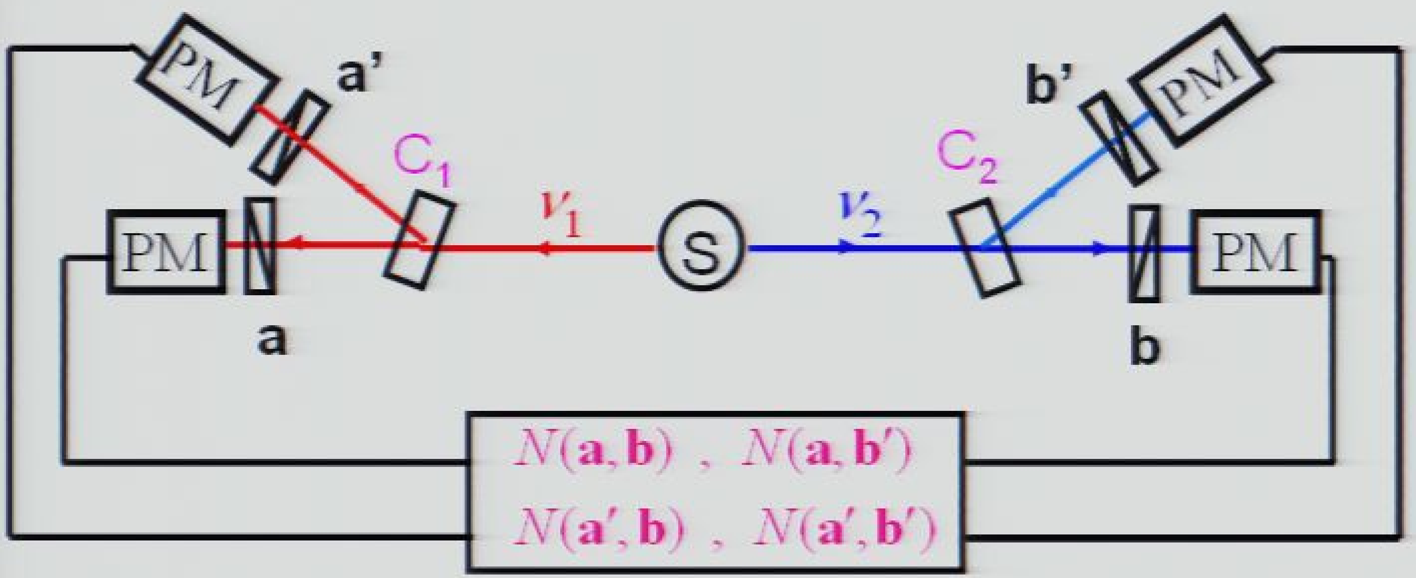

Switch C_1 redirects light
- either towards pol. in orient. **a**
- or towards pol. in orient. **a'**

Equivalent to a single polarizer switching between **a** and **a'**

Between two switching: 10 ns $< L/c \approx 40$ ns

Idem C_2 for **b** and **b'**

Experiment with variable polarizers: results AA, J. Dalibard, G. Roger, PRL 1982

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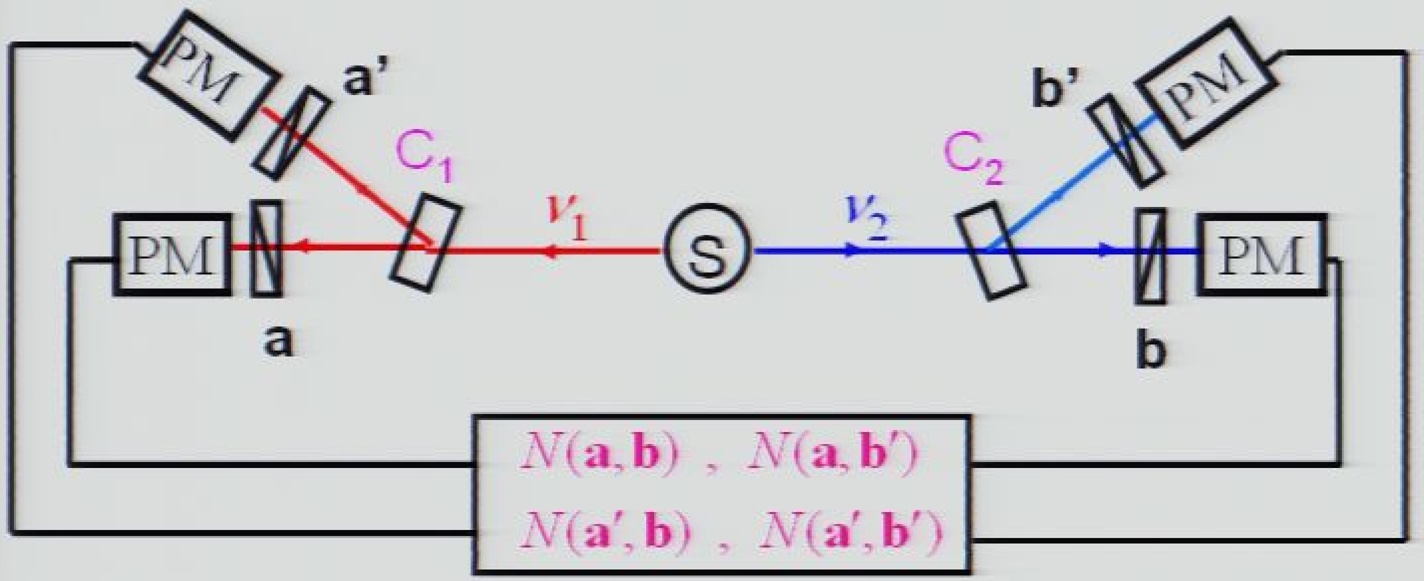
Acousto optical switch: change every 10 ns. Faster than propagation of light between polarizers (40 ns) and even than time of flight of photons between the source S and each switch (20 ns).



Difficult experiment: reduced signal; data taking for several hours; switching not fully random

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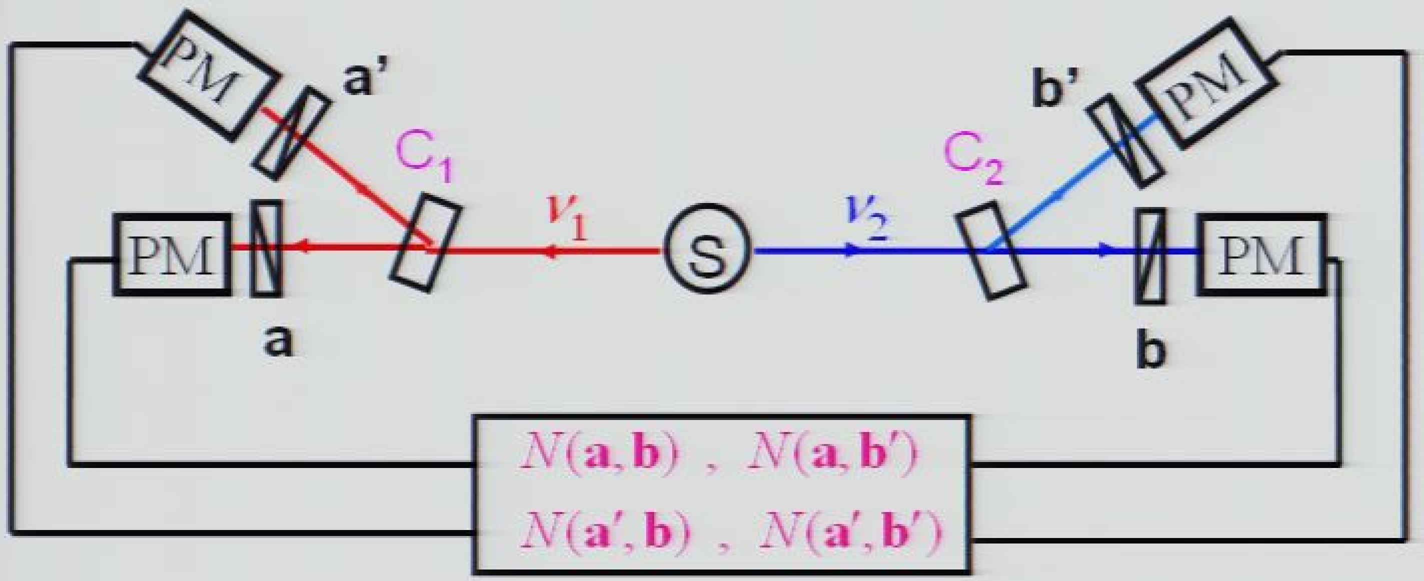
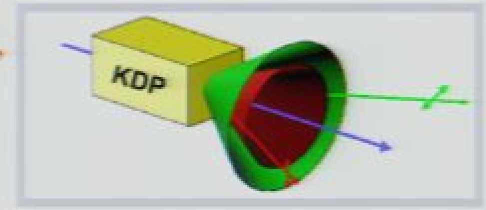


Difficult experiment: reduced signal; data taking for several hours; switching not fully random

Convincing result: Bell's inequalities violated by par 6 standard deviations. Each measurement space-like separated from setting of distant polarizer: Einstein's causality enforced

Third generation experiments

Entangled photon pairs by parametric down conversion, well defined directions: injected into optical fibers.

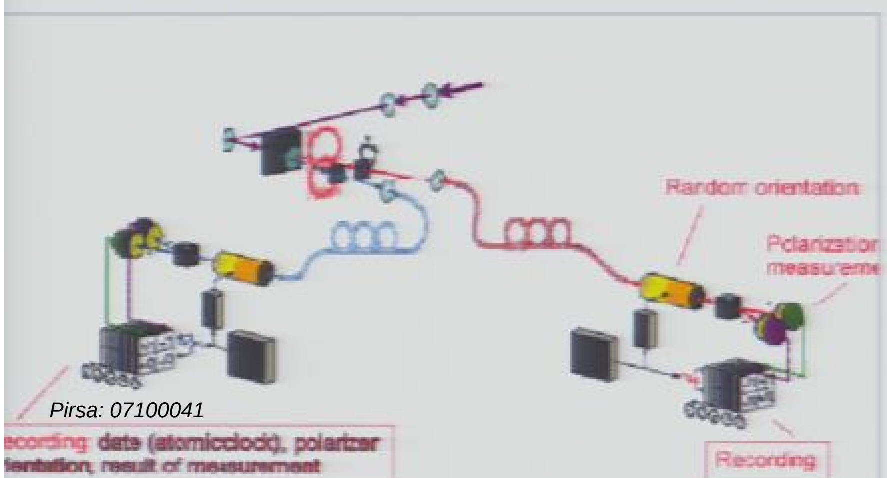


Entanglement at a very large distance

Geneva experiment (1998):

- Optical fibers of the commercial telecom network
- Measurements separated by 30 km

Agreement with QM.



Innsbruck experiment (1998):

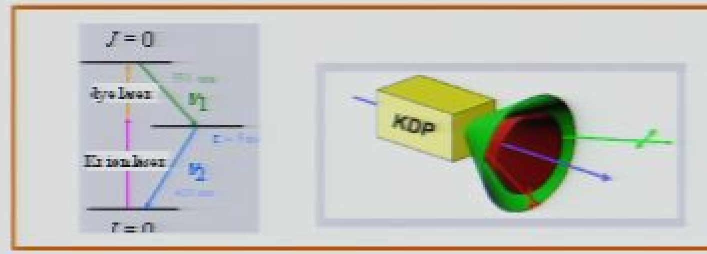
variable polarizers with orientation chosen by a random generator during the propagation of photons (several hundreds meters).

Agreement with QM.

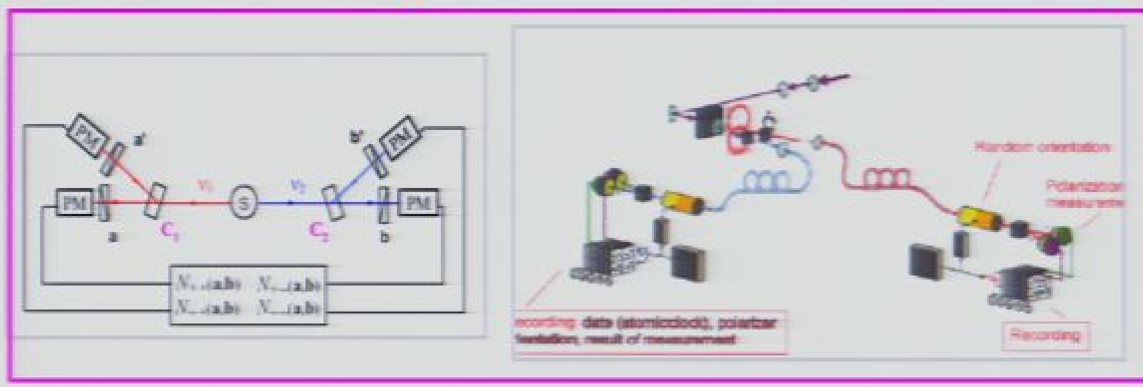
Bell's inequalities have been violated in almost ideal experiments

Results in agreement with quantum mechanics in experiments closer and closer to the GedankenExperiment:

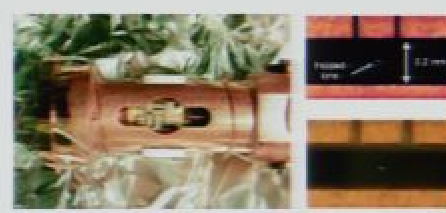
- Sources of entangled photons more and more efficient



- Relativistic separation of measurements (Orsay 1982, Innsbruck 1998): variable polarizers; closure of the locality loophole



- Experiment with trapped ions (Boulder 2000): closure of the "sensitivity loophole".



Einstein's local realism is untenable

The failure of local realism

Einstein had considered (in order to reject it) the consequences of the failure of the EPR reasoning:

- either drop the need of the independence of the physical realities present in different parts of space
- or accept that the measurement of S_1 changes (instantaneously) the real situation of S_2

Quantum non locality – Quantum holism

The properties of a pair of entangled particles are more than the addition of the individual properties of the constituents of the pairs (even space like separated). Entanglement = global property.

NB: no faster than light transmission of a "utilizable" signal

Entanglement: a resource for quantum information

The understanding of the extraordinary properties of entanglement has triggered a new research field: quantum information

Hardware based on different physical principles allows emergence of new concepts in information theory:

- Quantum computing (R. Feynman 1982, D. Deutsch 1985)
- Quantum cryptography (Bennett Brassard 84; Ekert 1991)

Entanglement is at the root of schemes for quantum information

- Quantum cryptography (Ekert scheme)
- Quantum gates: basic components of a "would be" quantum computer…

Quantum cryptography: sharing two identical copies of a secret key (QKD)

The goal: distribute to two partners (Alice et Bob) two identical secret keys (a random sequence of 1 and 0), with absolute certainty that no spy (Eve) has been able to get a copy of the key.

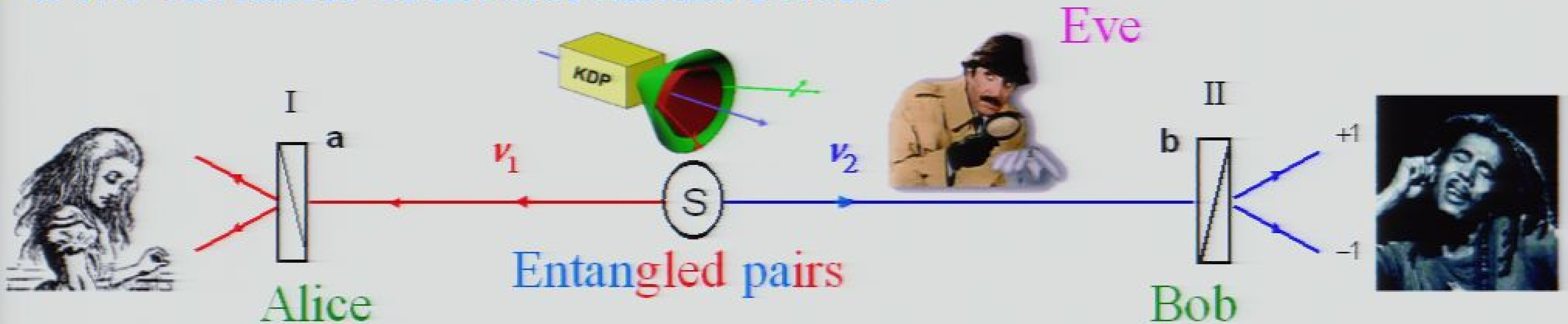
Using that key, Alice and Bob can exchange (publicly) a coded message with a mathematically proved safety (Shannon theorem) (provided the message is not longer than the key)

Two ways absolutely secure: single photons, pairs of entangled photons

Quantum cryptography with entangled pairs

Alice and Bob select their analysis directions **a** et **b** randomly among 2, make measurements, then send publicly:

- the list of all selected directions
- a sub ensemble of measurements results



Cases of a et **b** identical : identical results ⇒ 2 identical keys

There is nothing to spy on the entangled flying photons: the key is created at the moment of the measurement.

If Eve chooses a particular direction of analysis, makes a measurement, and reemits a photon according to her result, his maneuver leaves a trace that can be detected by doing a Bell's inequalities test

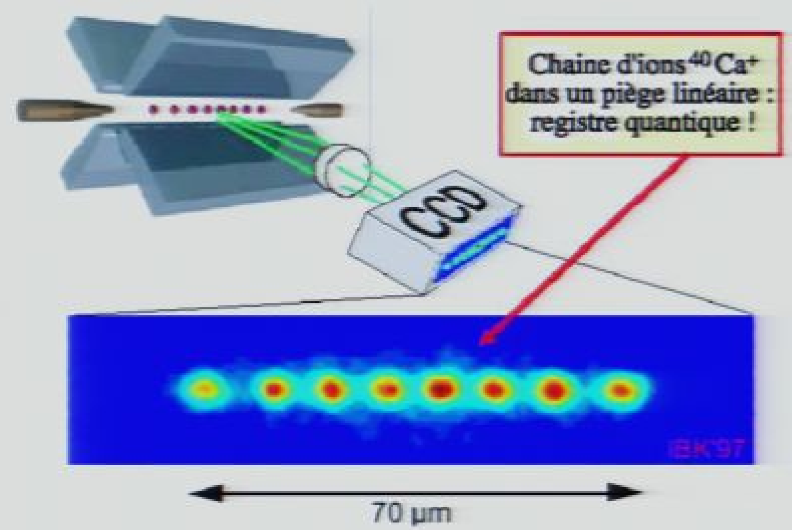
Quantum computing?

A quantum computer could operate new types of algorithms able to make calculations exponentially faster than classical computers.
Example: Shor's algorithm for factorization of numbers: the RSA encryption method would no longer be safe.

Fundamentally different hardware:
fundamentally different software.

What would be a quantum computer?

An ensemble of interconnected quantum gates, processing strings of entangled quantum bits (qubit: 2 level system)



Entanglement ⇒ massive parallelism

The Hilbert space to describe N entangled qubits has dimension 2^N !
(most of that space consists of entangled states)

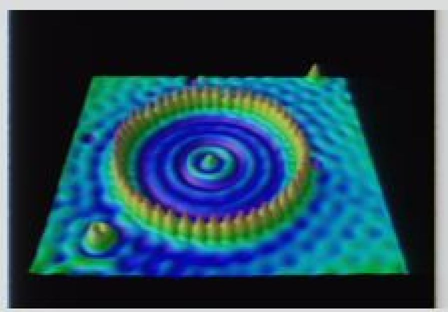
A new quantum age?

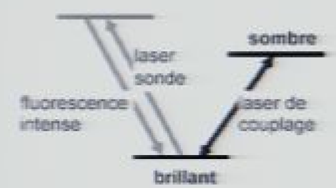
Entanglement

- A revolutionary concept, as guessed by Einstein and Bohr, strikingly demonstrated by Bell
- Drastically different from concepts underlying the first quantum revolution (wave particle duality).

At the root of a new quantum revolution, conceptually as amazing (if not more) as the first quantum revolution

Another important ingredient: the experimental control (and theoretical description) of individual quantum objects (electrons, atoms, ions, photons)





Towards a new technological revolution?

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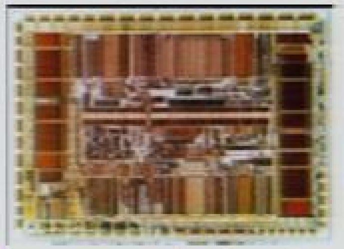

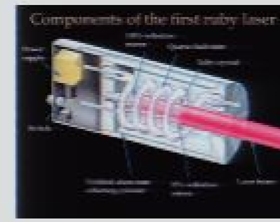

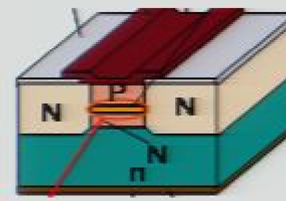

Will the new quantum revolution (entanglement + individual quantum systems) give birth to a new technological revolution based on quantum communication and quantum computers ?

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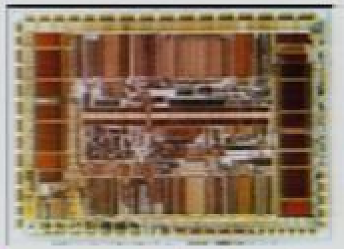

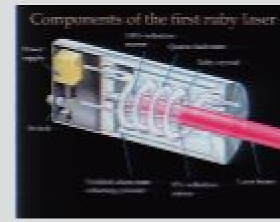

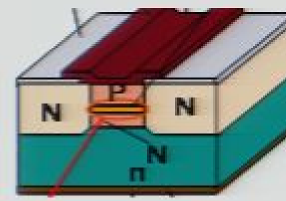

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Will the new quantum revolution (entanglement + individual quantum systems) give birth to a new technological revolution based on quantum communication and quantum computers ?

The most likely roadmap (as usual): from proofs of principle with well defined elementary microscopic objects (photons, atoms, ions, molecules…) to solid state devices (and continuous variables?) …

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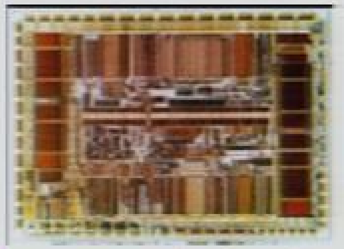

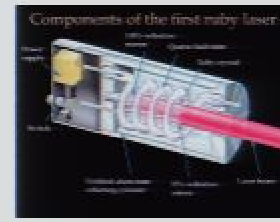

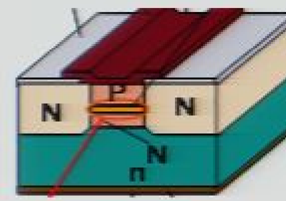

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A fascinating issue… we live exciting times!

INSTITUT d'OPTIQUE GRADUATE SCHOOL

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

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to those who encouraged me at a time when "Bell's inequalities" was not a section of the PACS classification index

and to all the colleagues who have reacted to the idea of a 2nd quantum revolution

* (in 1981- 82)

PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS