From Einstein's intuition to quantum bits: a new quantum age?
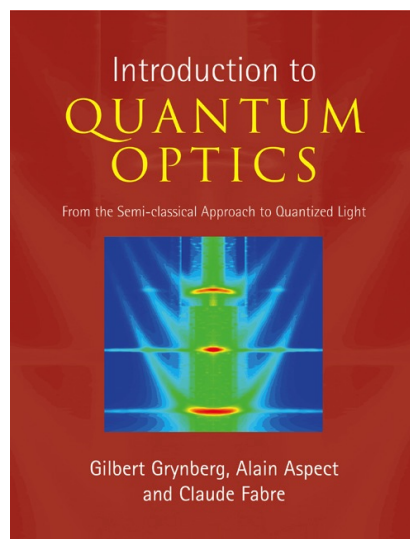
Alain ASPECT - Institut d'Optique - Palaiseau

ICTP colloquium, Trieste
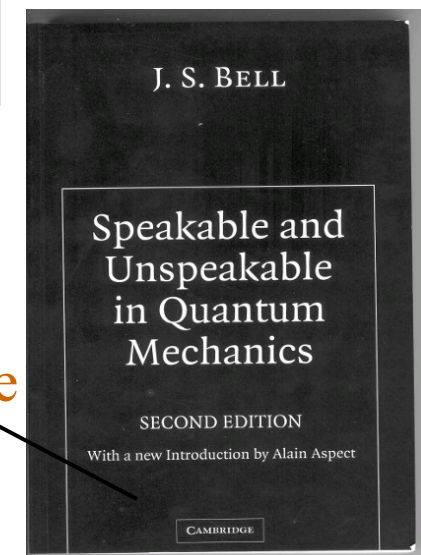
August 20, 2013

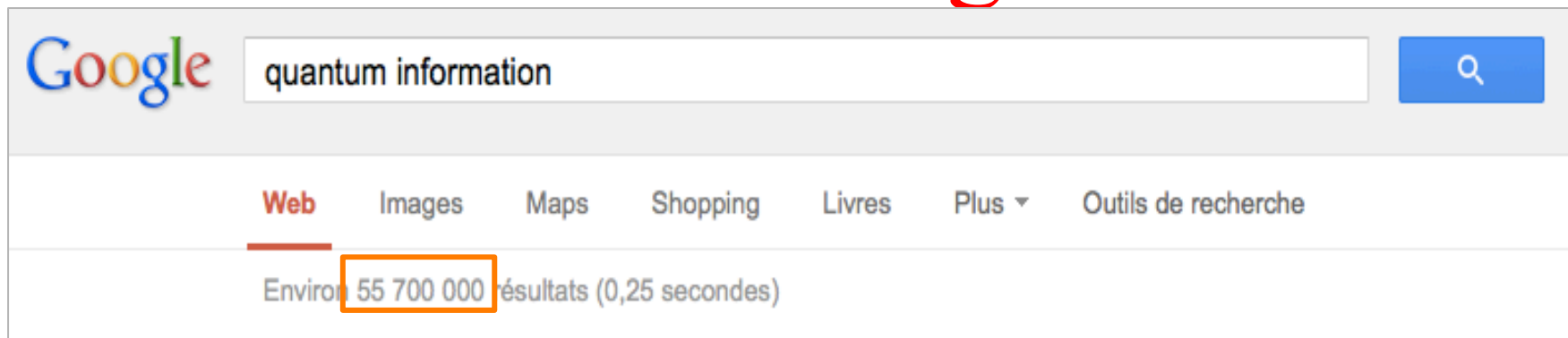AA: "Bell's theorem: the naïve view of an experimentalist" quant-ph/0402001

AA: "John Bell and the second quantum revolution" in "Speakable and Unspeakable in Quantum Mechanics" (Cambridge University Press 2004).

CUP 2010

CUP 2004

http://www.lcf.institutoptique.fr/Alain-Aspect-homepage

1

Quantum information
a flourishing field

Quantum information
How did it emerge?

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)

OCTOBER 15, 1935   PHYSICAL REVIEW   VOLUME 48

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

N. BOHR, *Institute for Theoretical Physics, University, Copenhagen*
(Received July 13, 1935)

Proceedings of the Cambridge Philosophical Society, 1935 - hep.princeton.edu

DISCUSSION OF PROBABILITY RELATIONS BETWEEN SEPARATED SYSTEMS

BY E. SCHRÖDINGER

[Communicated by Mr M. BORN]

[*Received* 14 August, *read* 28 October 1935]

Entanglement is different!

Physics Vol. 1, No. 3, pp. 195–290, 1964   Physics Publishing Co.   Printed in the United States

ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

J. S. BELL[†]

Department of Physics, University of Wisconsin, Madison, Wisconsin
[†]On leave of absence from SLAC and CERN

3

Quantum information
How did it emerge?

In this chapter we shall tackle immediately the basic element of the mysterious behavior in its most strange form. We choose to examine a phenomenon which is impossible, *absolutely* impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the *only* mystery. (1960)

I've entertained myself always by squeezing the difficulty of quantum mechanics into a smaller and smaller place, so as to get more and more worried about this particular item. It seems to be almost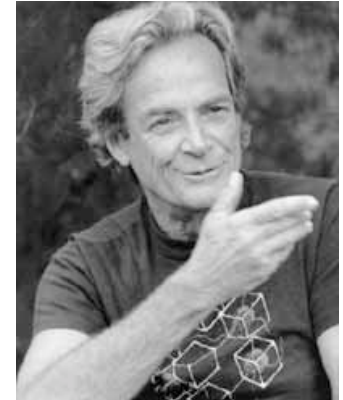 ridiculous that you can squeeze it to a numerical question that one thing is bigger than another. But there you are – it is bigger..." (1982)

Entanglement is different

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

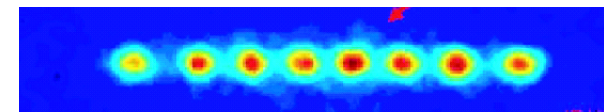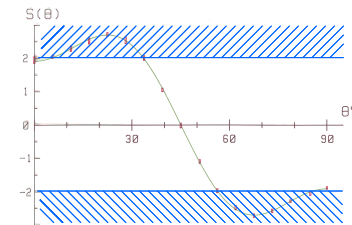## Simulating Physics with Computers

Richard P. Feynman (1982)

Department of Physics, California Institute of Technology, Pasadena, California 91107

Entanglement is more

From Einstein's intuitions to qubits

1. From Einstein-Podolsky -Rosen to Bell

2. Experimental tests of Bell's inequalities with correlated photons

3. A new quantum age?

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 one to envisage 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 at the core of quantum information (198x-20??)

# The EPR question

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

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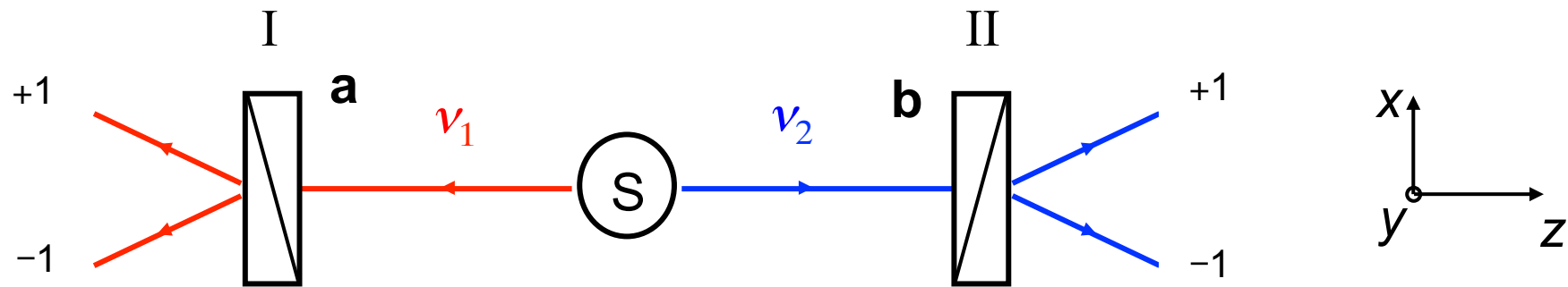
Measurement of the polarization of ν_1 along orientation **a** and and of polarization of ν_2 along orientation **b** : results +1 or −1

Þ 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
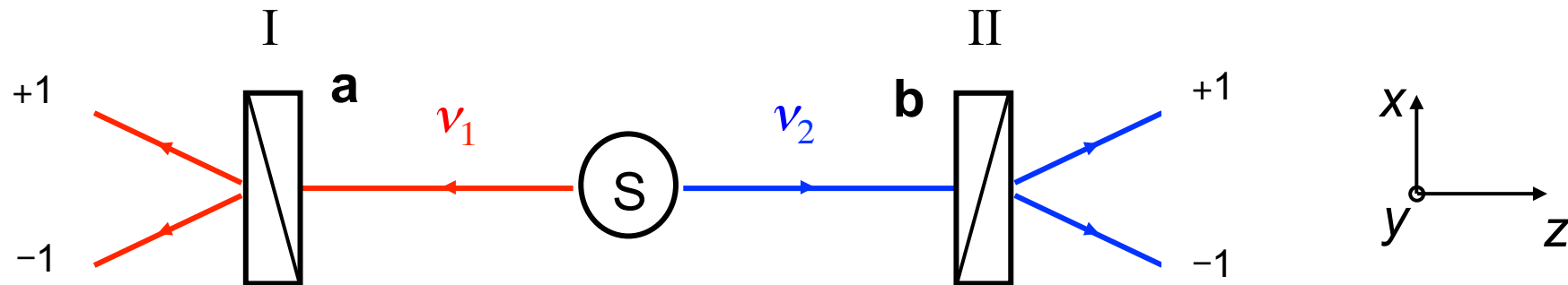
For the entangled EPR state…

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

Quantum mechanics predicts results separately random …

$$P_+(\mathbf{a}) = P_-(\mathbf{a}) = \frac{1}{2} \; ; \; P_+(\mathbf{b}) = P_-(\mathbf{b}) = \frac{1}{2}$$
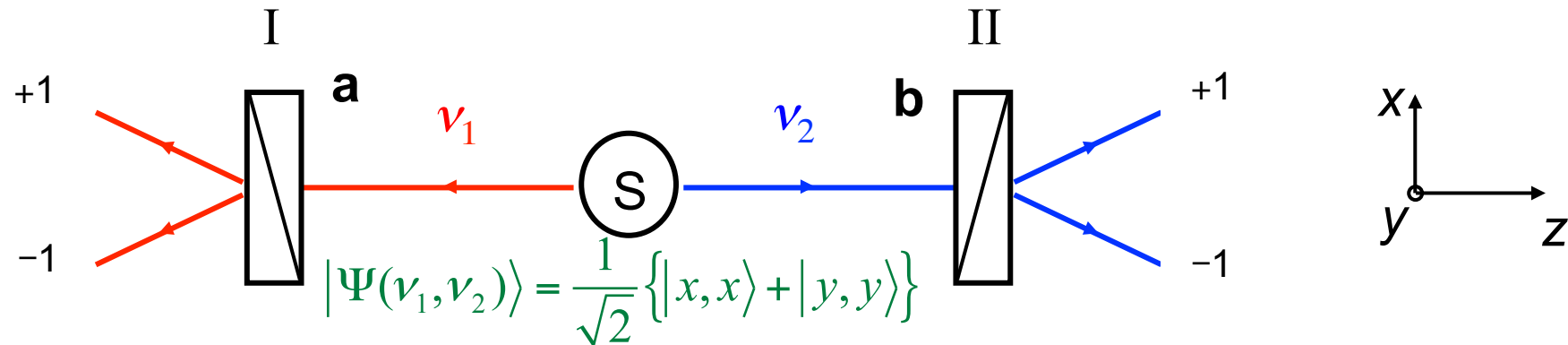
but strongly correlated:

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

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

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

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

Coefficient of correlation of polarization (EPR state)

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

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

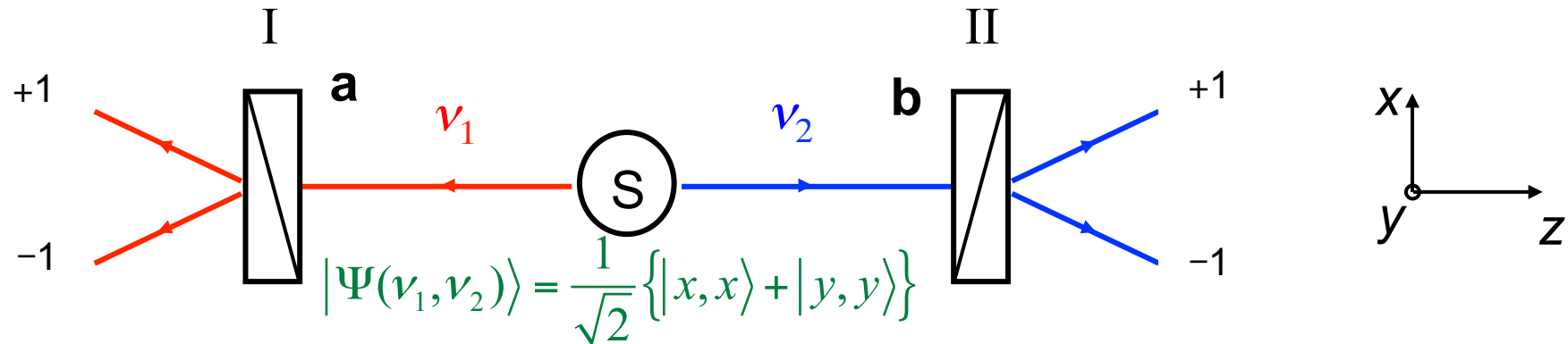$$E = P_{++} + P_{--} - P_{+-} - P_{-+} = P(\text{résutats id°}) - P(\text{résutats} \neq)$$

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

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

$$P_{+-} = P_{-+} = 0 \qquad \text{Total correlation}$$

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?

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

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

Can we derive an image from the QM calculation?

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

Can we derive an image from the QM calculation?

The direct calculation $P_{++}(\mathbf{a},\mathbf{b}) = \left| \left\langle +_{\mathbf{a}}, +_{\mathbf{b}} \middle| \Psi(\nu_1,\nu_2) \right\rangle \right|^2 = \frac{1}{2}\cos^2(\mathbf{a},\mathbf{b})$ is done in an abstract 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:

$$\left| \Psi(\nu_1,\nu_2) \right\rangle = \frac{1}{\sqrt{2}}\left\{ \left| x,x \right\rangle + \left| y,y \right\rangle \right\} \neq \left| \phi(\nu_1) \right\rangle \cdot \left| \chi(\nu_2) \right\rangle$$
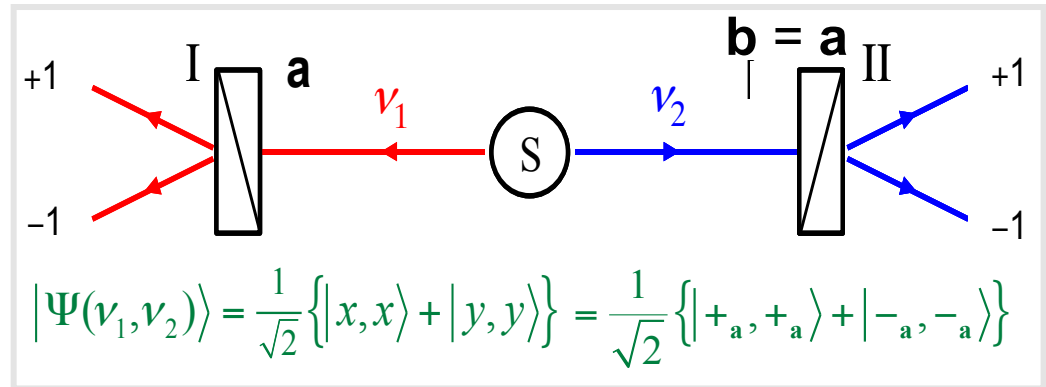
One cannot identify properties attached to each photon separately

"Quantum phenomena do not occur in a Hilbert space, they occur in a laboratory" (A. Peres) $\Rightarrow$ An image in real space?

A real space image of the EPR correlations derived from a quantum calculation

2 step calculation (standard QM)

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

1) Measure on ν_1 by I (along **a**)

$\Rightarrow$ result $+1$ $\left|+_a\right\rangle$

or

$\Rightarrow$ result -1 $\left|-_a\right\rangle$

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

$\left|+_a,+_a\right\rangle$

or

$\left|-_a,-_a\right\rangle$

2) Measure on ν_2 by II (along **b = a**)

- If one has found $+1$ for ν_1 then the state of ν_2 is $\left|+_a\right\rangle$ and the measurement along **b = a** yields $+1$;
- If one has found -1 for ν_1 then the state of ν_2 is $\left|-_a\right\rangle$ and the measurement along **b = a** yields -1;

Easily generalized to **b ≠ a** (Malus law)

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.
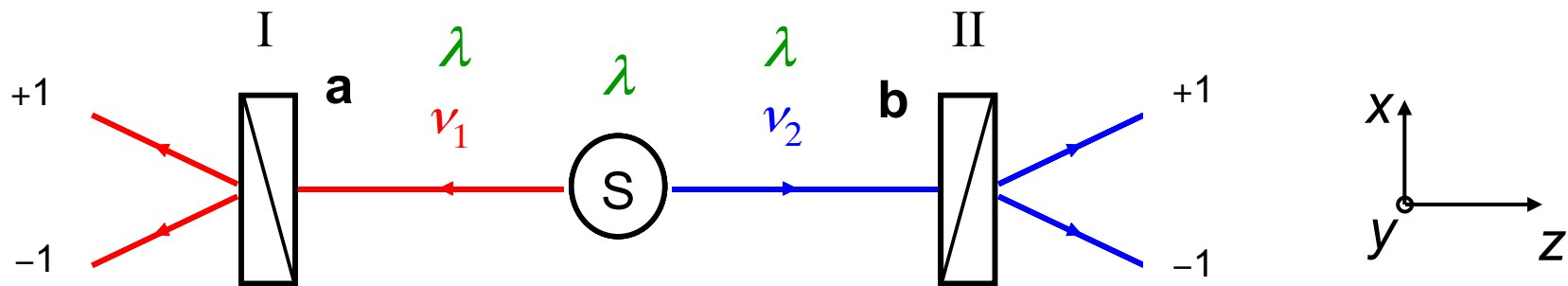
exemple

$\lambda = +_a$

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 (later: laser, integrated circuits…)

- No disagreement on the validity of quantum predictions, only on its interpretation.

1964: Bell's formalism
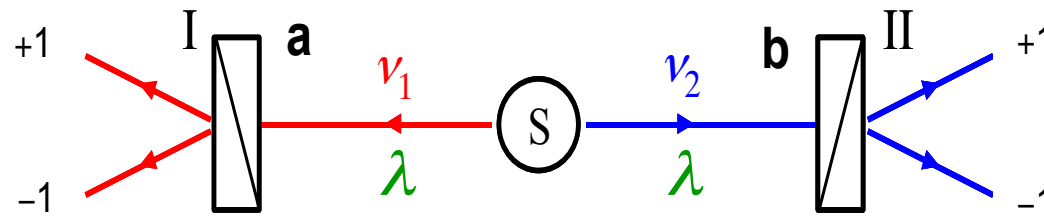
Consider local supplementary parameters theories (in the spirit of Einstein's ideas on EPR correlations):

- 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 $\Longleftrightarrow$

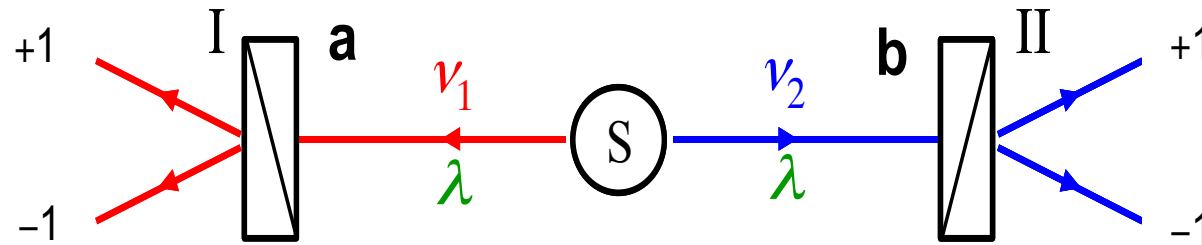$$A(\lambda, \mathbf{a}) = +1 \text{ or } -1 \text{ at polarizer I}$$

$$B(\lambda, \mathbf{b}) = +1 \text{ or } -1 \text{ at polarizer II}$$

- The supplementary parameter λ is randomly distributed among pairs $\Longleftrightarrow$

$$\rho(\lambda) \geq 0 \quad \text{and} \quad \int \rho(\lambda)\, d\lambda = 1$$

at source S

$$E(\mathbf{a}, \mathbf{b}) = \int d\lambda\, \rho(\lambda)\, A(\lambda, \mathbf{a}) B(\lambda, \mathbf{b})$$

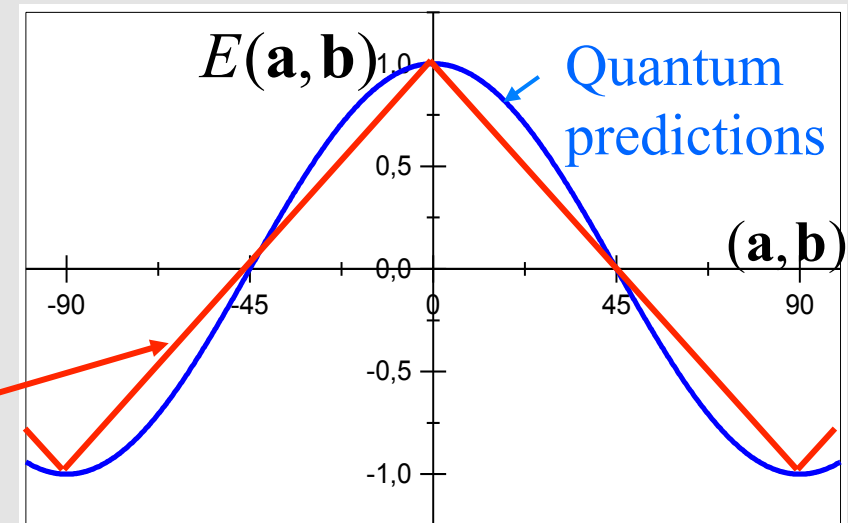# 1964: Bell's formalism to explain correlations

An example

- Common polarisation λ, randomly distributed among pairs $\rho(\lambda) = 1/2\pi$

- Result (± 1) depends on the angle between λ and polarizer orientation (**a** or **b**)

$$A(\lambda, \mathbf{a}) = \text{sign}\left\{\cos 2(\theta_\mathbf{a} - \lambda)\right\}$$

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

Resulting correlation

Not bad, but no exact agreement

Is there a better model, agreeing with QM predictions at all orientations?

Bell's theorem gives the answer

Bell's theorem

No!

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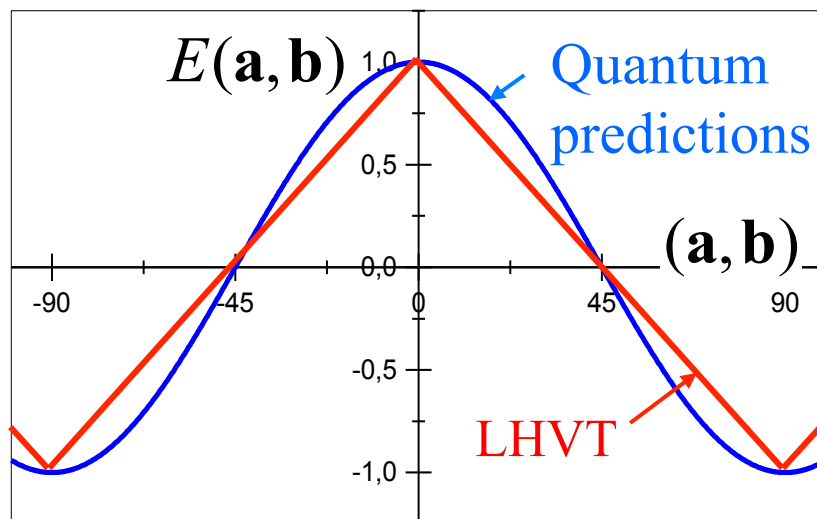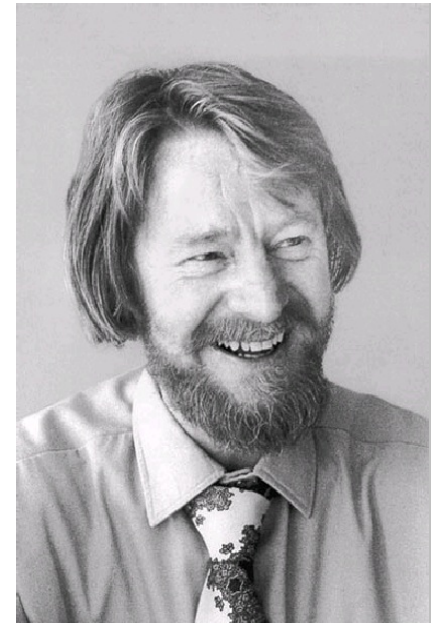
Impossible to cancel the difference everywhere

Impossible to have quantum predictions exactly reproduced at *all* orientations, by any model à la Einstein

Bell's inequalities are violated by certain quantum predictions

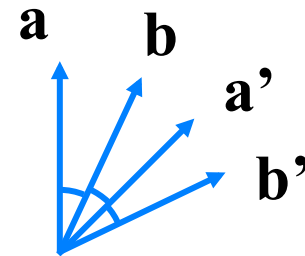Any local hidden variables theory $\Rightarrow$ Bell's inequalities

$-2 \leq S \leq 2$ 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 $\quad E_{MQ}(\mathbf{a}, \mathbf{b}) = \cos 2(\mathbf{a}, \mathbf{b})$

For orientations $\quad (\mathbf{a}, \mathbf{b}) = (\mathbf{b}, \mathbf{a}') = (\mathbf{a}', \mathbf{b}) = \dfrac{\pi}{8}$
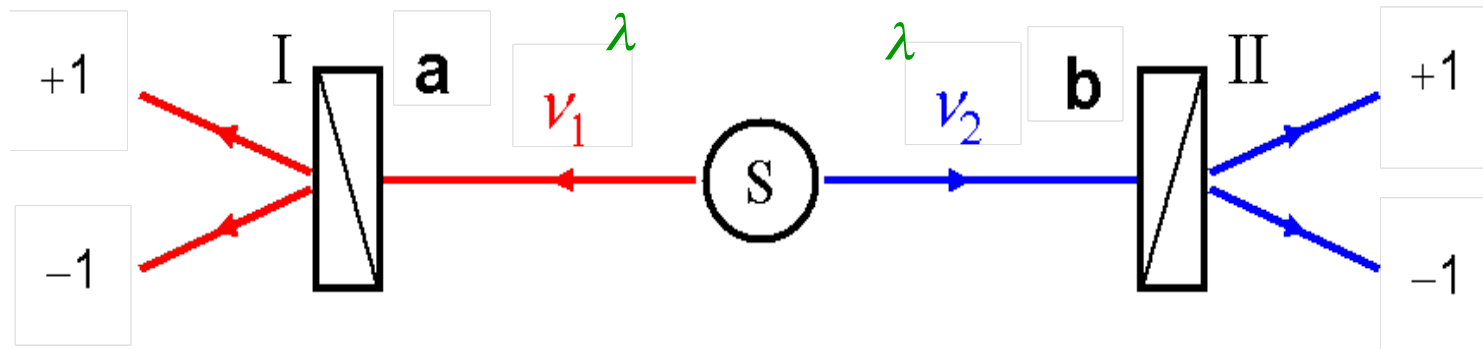
$S_{QM} = 2\sqrt{2} = 2.828... > 2$

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

Conditions for a conflict
($\Rightarrow$ 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 $\mathbf{b}$ of distant polarizer II (and conv.)

• The distribution $\rho(\lambda)$ of supplementary parameters over
  the pairs does not depend on the orientations $\mathbf{a}$ and $\mathbf{b}$.

Bell's locality condition

$$A(\lambda, \mathbf{a}, \mathbf{b}) \qquad B(\lambda, \mathbf{a}, \mathbf{b}) \qquad \rho(\lambda, \mathbf{a}, \mathbf{b})$$

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)

cf. Bohm & Aharonov, Physical Review, 1957
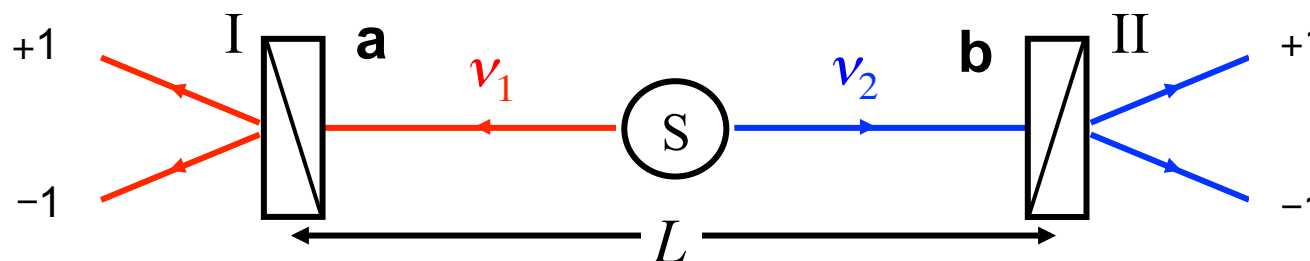
Conflict between quantum mechanics and Einstein's world view (local realism based on relativity).

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 find a situation where the test is possible: CHSH proposal (1969)

Three generations of experiments

Pioneers (1972-76): Berkeley, Harvard, Texas A&M
- First results contradictory (Clauser = QM; Pipkin ≠ QM)
- Clear trend in favour of Quantum mechanics (Clauser, Fry)
- Experiments 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
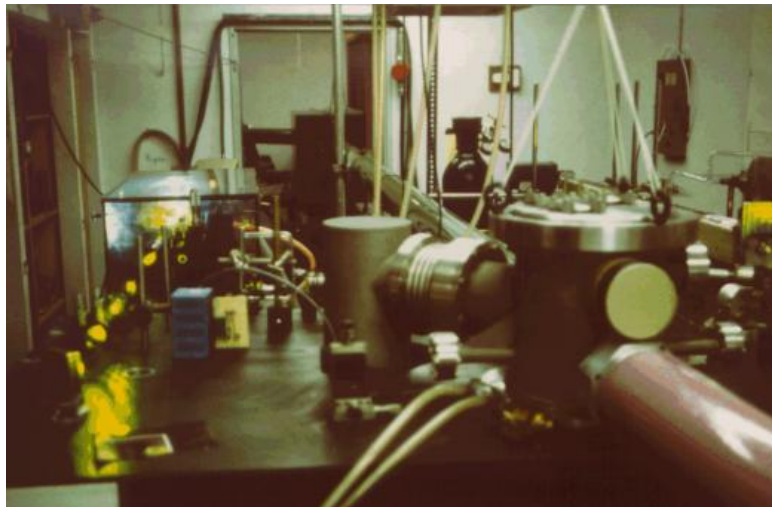- Test of quantum non locality (relativistic separation)

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

Institut d'Optique

$J = 0$

551 nm
ν_1
dye laser

$J = 1$
$\tau_r = 5$ ns

Kr ion laser
ν_2
423 nm

$J = 0$
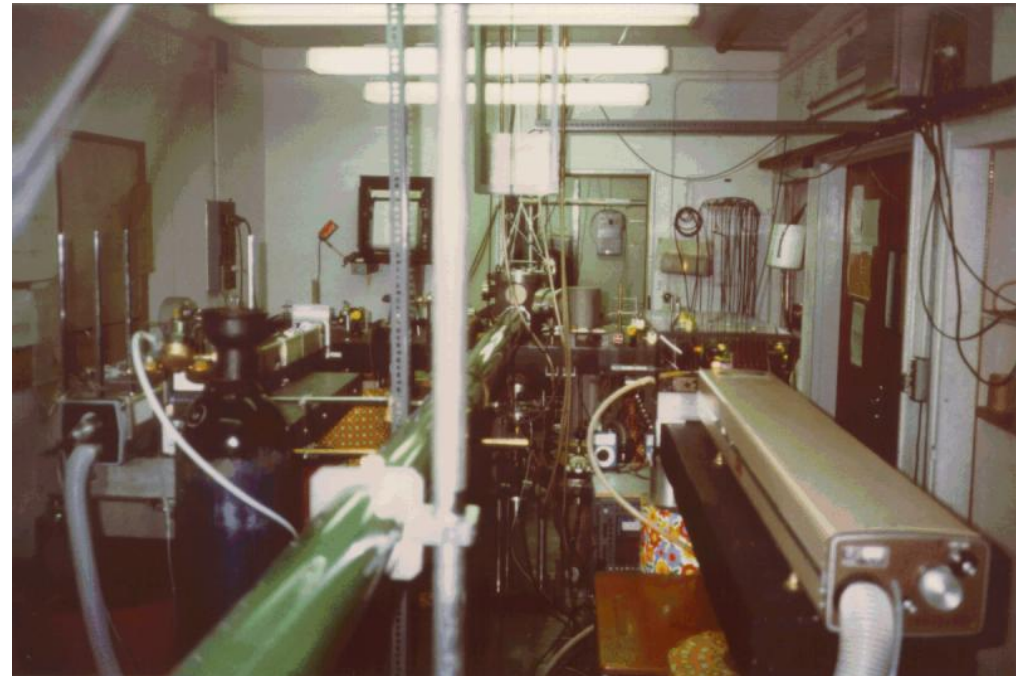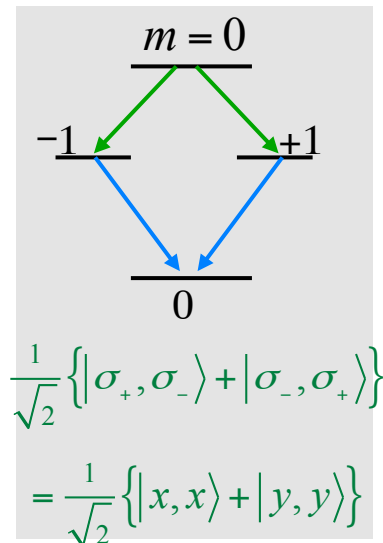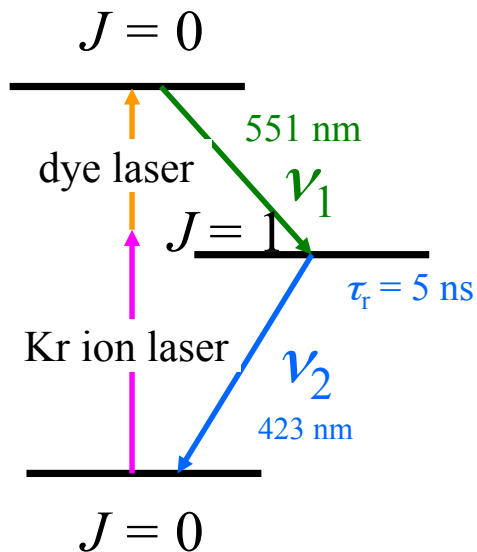
Two photon selective excitation

$m = 0$

-1 $+1$

0

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

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

☺ 100 coincidences per second
1% precision for 100 s counting

Polarizers at 6 m from the source:
violation of Bell's inequalities,
entanglement survives "large" distance

24

Experiment with 2-channel polarizers (AA, P. Grangier, G. Roger, 1982)
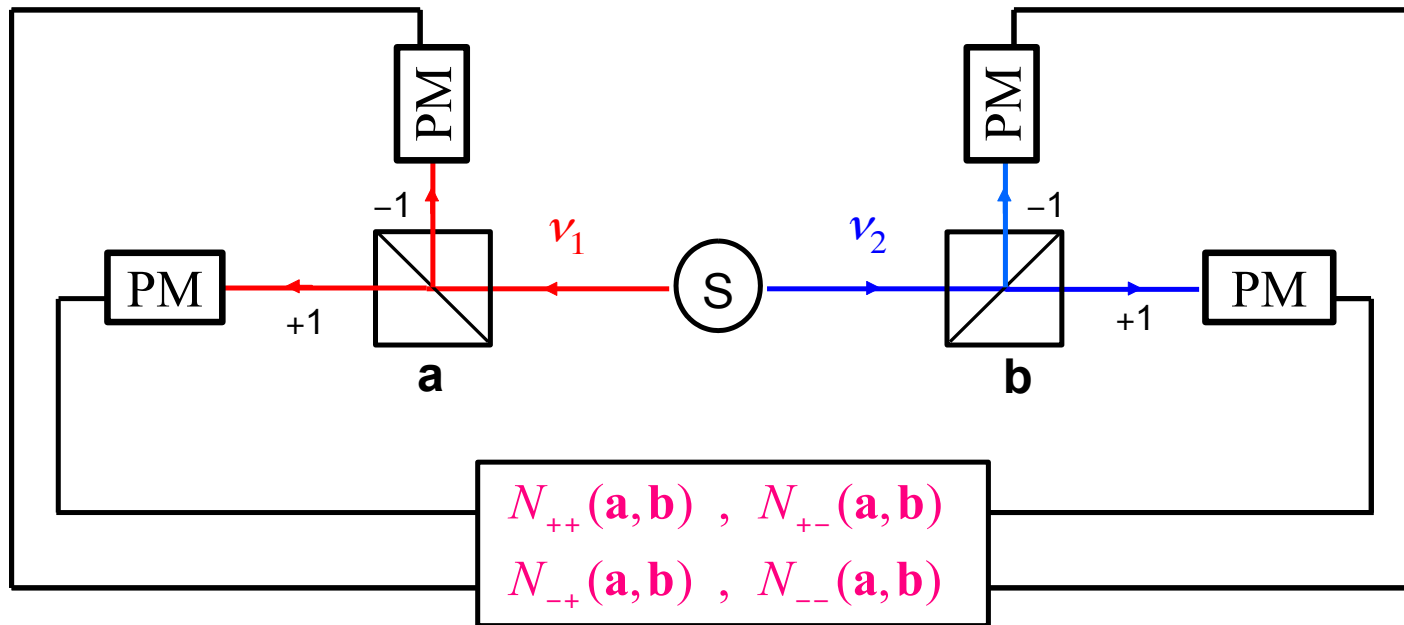
$$N_{++}(\mathbf{a},\mathbf{b}) \;,\; N_{+-}(\mathbf{a},\mathbf{b})$$
$$N_{-+}(\mathbf{a},\mathbf{b}) \;,\; N_{--}(\mathbf{a},\mathbf{b})$$

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)

Bell's limits

⊡ Measured value ± 2 standard dev.

— Quantum mechanical prediction (including imperfections of real experiment)
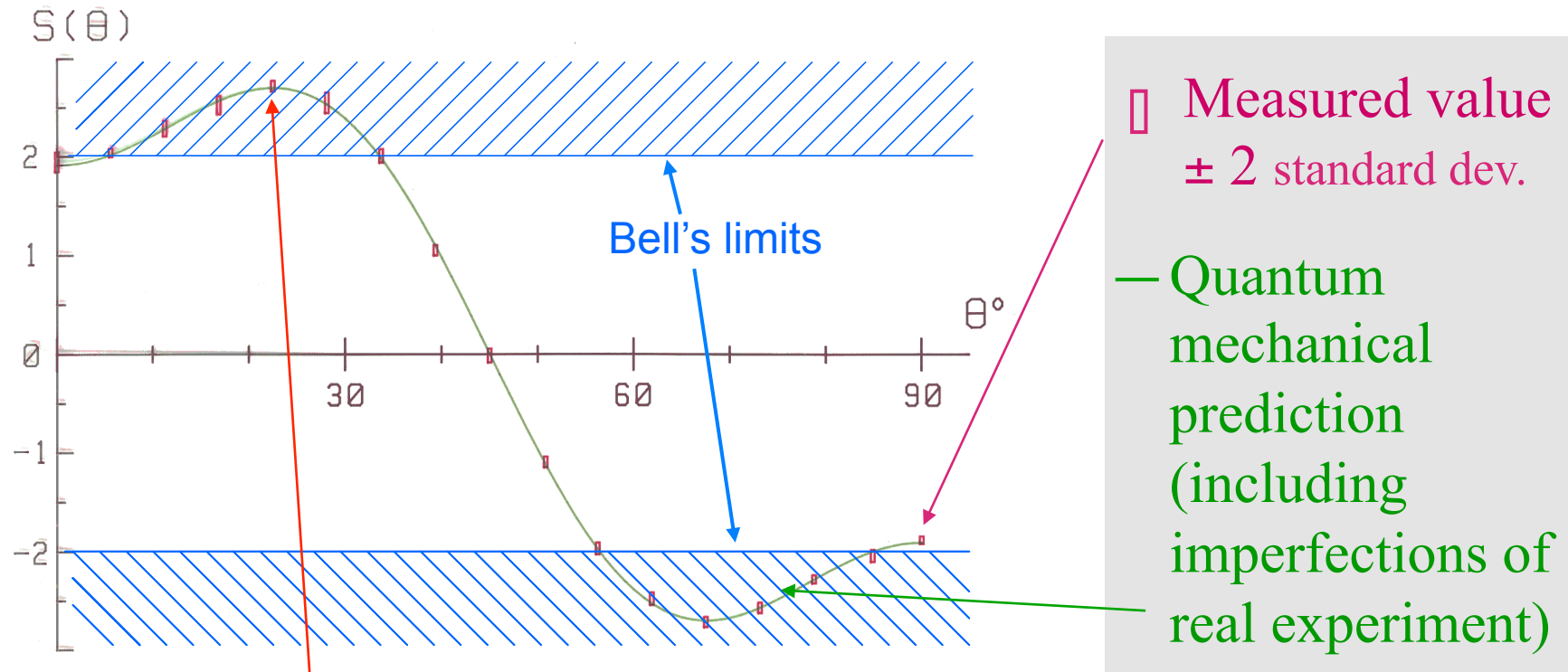
For $\theta = (\mathbf{a}, \mathbf{b}) = (\mathbf{b}, \mathbf{a'}) = (\mathbf{a'}, \mathbf{b}) = 22.5°$ $S_{\exp}(\theta) = 2.697 \pm 0.015$

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

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

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)

☹ Not realist with massive polarizer

☺ Possible with optical switch

$$N(\mathbf{a},\mathbf{b}) \ , \ N(\mathbf{a},\mathbf{b'})$$
$$N(\mathbf{a'},\mathbf{b}) \ , \ N(\mathbf{a'},\mathbf{b'})$$
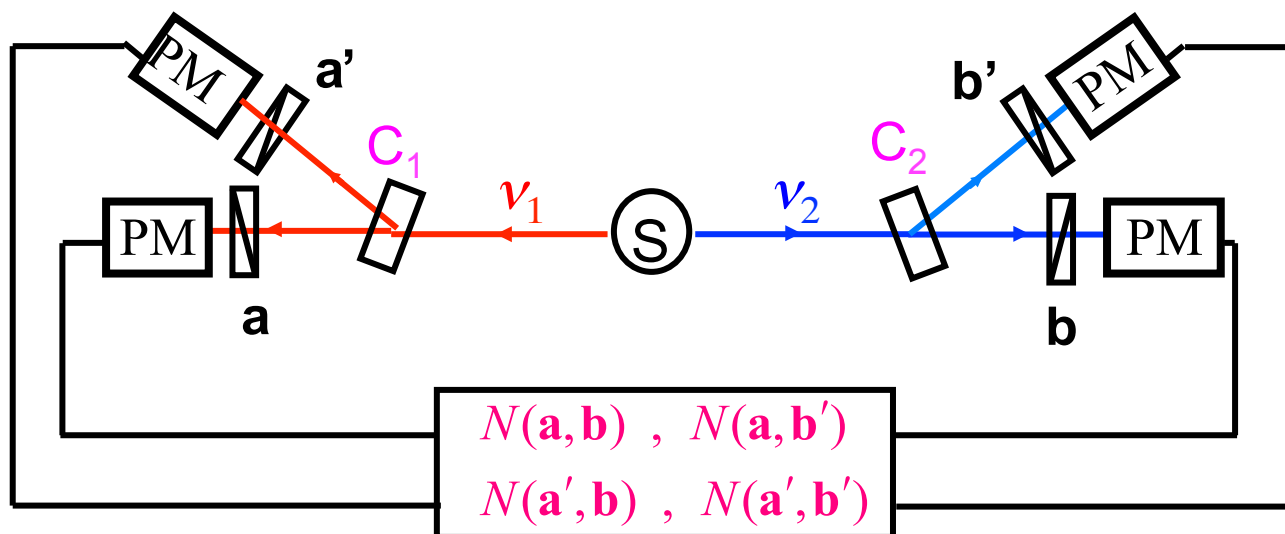
Between two switching: 10 ns $< L/c \approx 40$ ns

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'**

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

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

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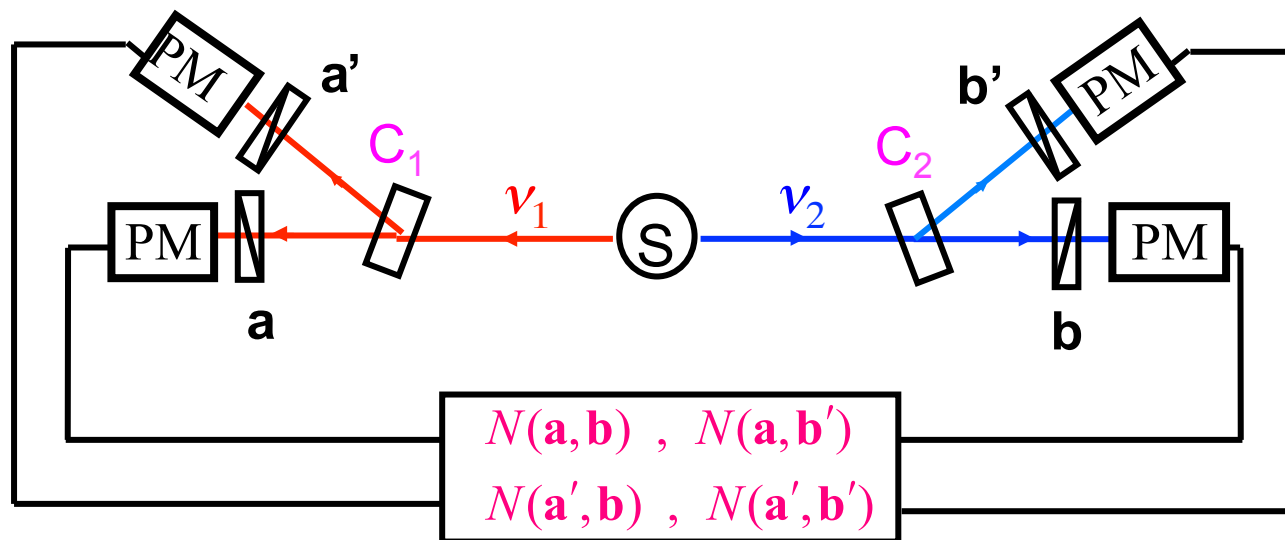
Difficult experiment: reduced signal; data taking for several hours; switching not fully random

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
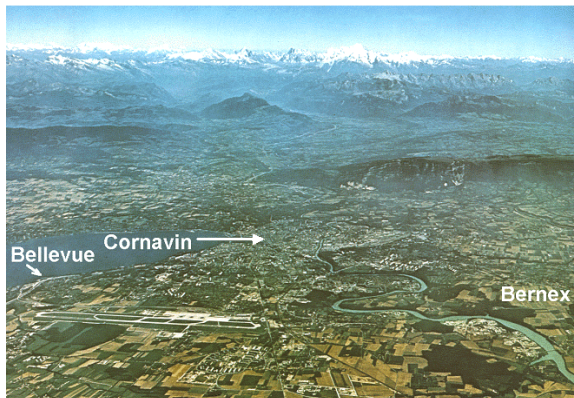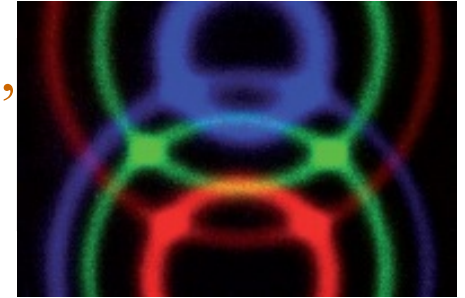
Geneva experiment (1998):
- Optical fibers of the commercial telecom network
- Measurements separated by 30 km

Agreement with QM.
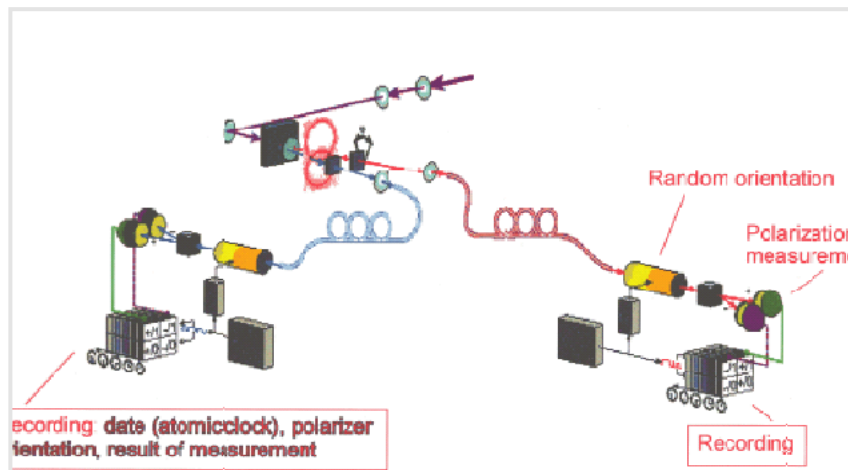
Innsbruck experiment (1998): variable polarizers with orientation chosen by a random generator during the propagation of photons (several hundreds meters).
Agreement with QM.

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 with variable polarizers (Orsay 1982, Innsbruck 1998); closure of locality loophole

- Experiment with trapped ions (Boulder 2000): closure of the "sensitivity loophole".
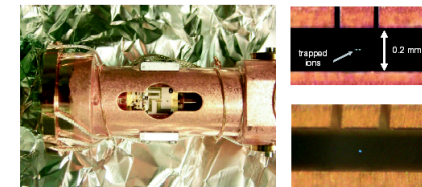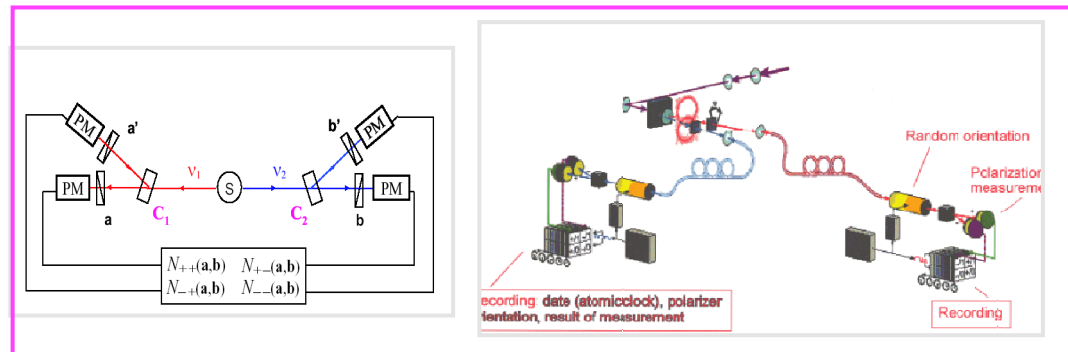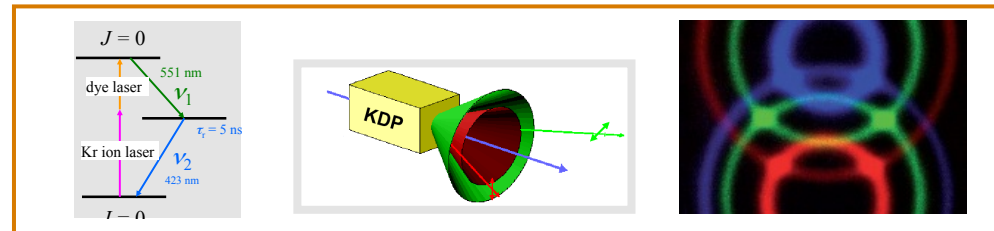
Einstein's local realism is untenable

The failure of local realism

Einstein had considered (in order to reject it by *reductio ad absurdum*) the consequences of the failure of the EPR reasoning: [If quantum mechanics could not be completed, one would have to]

- 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 (ask!)

Entanglement: a resource for quantum information

The understanding of the extraordinary properties of entanglement and its generalization to more than two particles (GHZ) 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)
- Quantum teleportation (BB&al., 1993; Innsbruck 1997; Roma)

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 teleportation

Quantum Key Distribution with entangled photons (Ekert)

Alice and Bob select their analysis directions **a** et **b** randomly among 2, make measurements, then send publicly the list of all selected directions

Eve

Entangled pairs

Alice

Bob
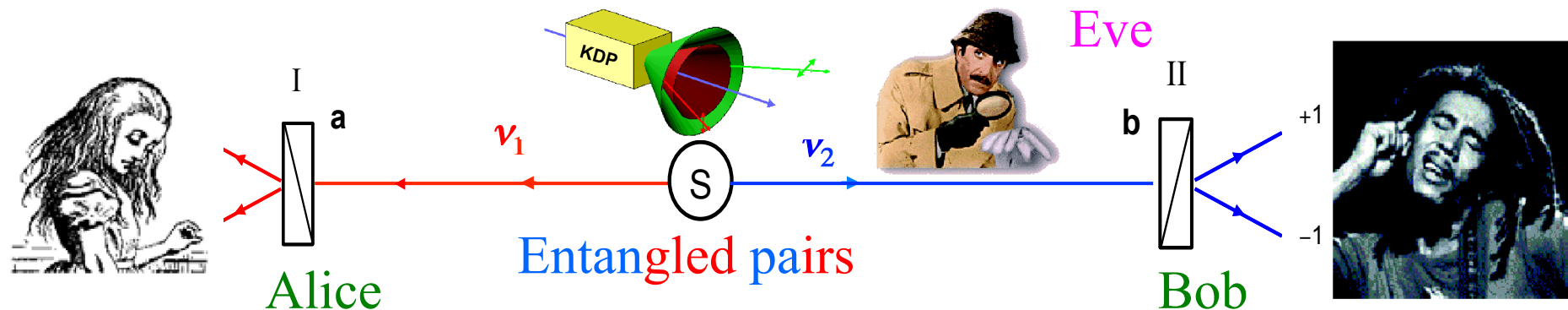
Cases of a et **b** identical : identical results $\Rightarrow$ 2 identical keys

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.

QKD at large distance, from space, on the agenda

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)

Chaine d'ions ^{40}Ca$^+$ dans un piège linéaire : registre quantique !

70 μm
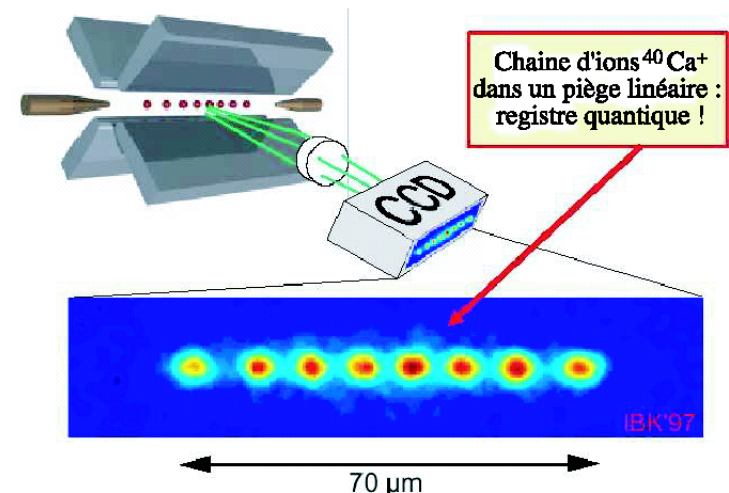
Entanglement ⇒ massive parallelism

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

A new quantum age

Two concepts at the root of a new quantum era

Entanglement

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

Individual quantum objects

- experimental control
- theoretical description (quantum Monte-Carlo)

Examples: electrons, atoms, ions, single photons, photons pairs

échantillon

"scanner" piezo. x,y,z

Objectif de microscope x 100, ON=1.4

Miroir dichroïque

Laser d'excitation

Filtre réjectif   diaphragme 50 µm   Module comptage de photon

APD Si

Fluorescence (counts/0.2 s)

Time (s)

laser sonde

fluorescence intense

sombre

laser de couplage

brillant
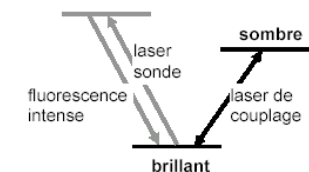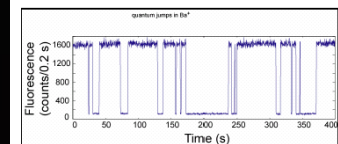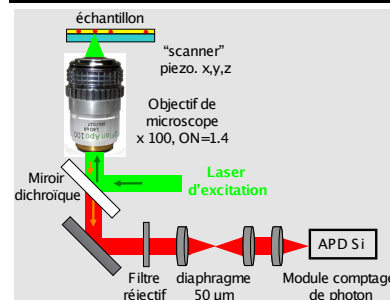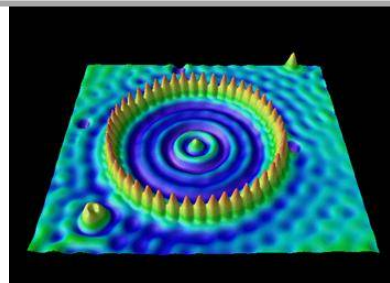
Towards a new technological revolution?

Will the new conceptual revolution (entanglement + individual quantum systems) give birth to a new technological revolution?
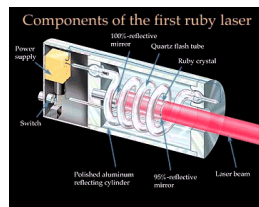
First quantum revolution (wave particle duality): lasers, transistors, integrated circuits ⇒ "information society"
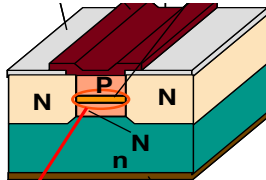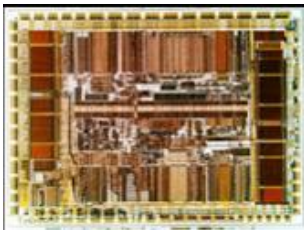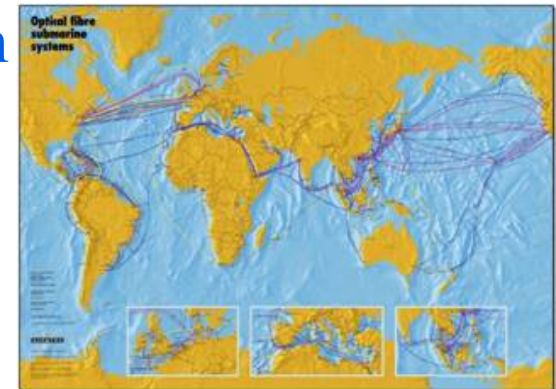
Will quantum computers and quantum communication systems lead to the "quantum information society"?

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?) …

A fascinating issue…   we live exciting times!

Acknowledgements

Thanks to the brave young* students whose involvement and enthusiasm were crucial to complete the 1982 experiments

Jean Dalibard   Philippe Grangier

to Gérard Roger and André Villing whose ingenuity made the Institut d'Optique experiment stable enough to produce reliable results

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

* (in 1981- 82)

Bell's inequalities at the lab classes of the Institut d'Optique Graduate School
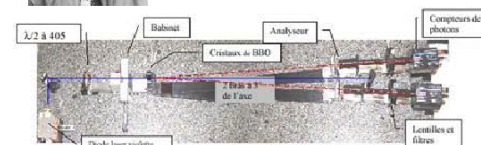
http://www.institutoptique.fr/telechargement/inegalites_Bell.pdf

Appendix

No faster than light signaling with EPR pairs

No faster than light signaling with EPR entangled pairs
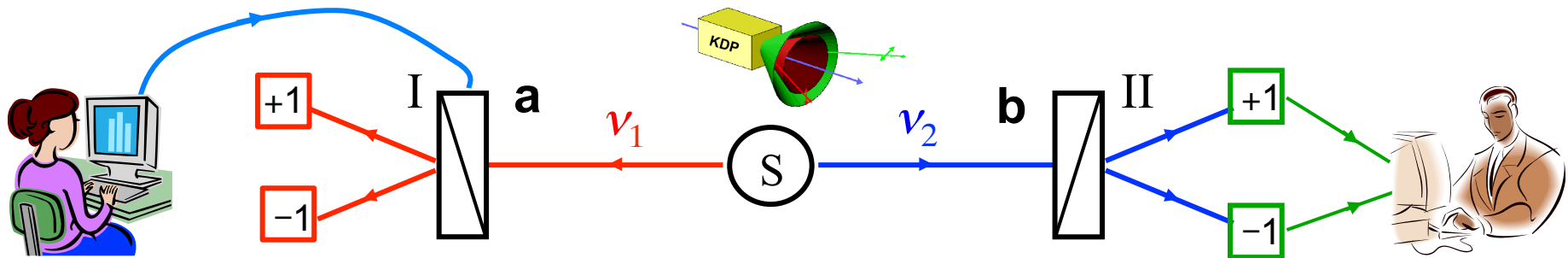
Alice changes the setting of polarizer I from **a** to **a'**: can Bob instantaneously observe a change on its measurements at II ?
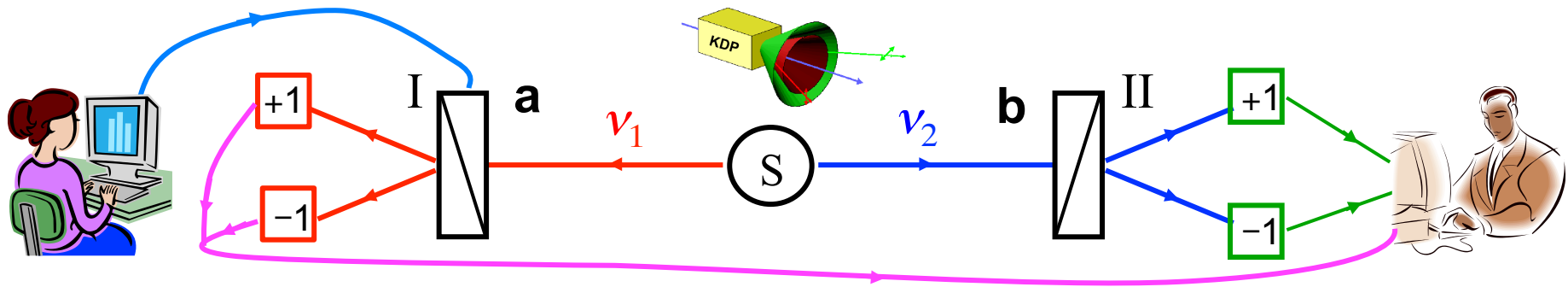
Single detections: $P_+(\mathbf{b}) = P_-(\mathbf{b}) = 1/2$ No information about **a**

Joint detections: $P_{++}(\mathbf{a},\mathbf{b}) = P_{--}(\mathbf{a},\mathbf{b}) = \dfrac{1}{2}\cos^2(\mathbf{a},\mathbf{b})$ etc.

Instantaneous change !

Faster than light signaling ?

No faster than light signaling with EPR entangled pairs

Alice changes the setting of polarizer I from **a** to **a'**: can Bob instantaneously observe a change on its measurements at II ?
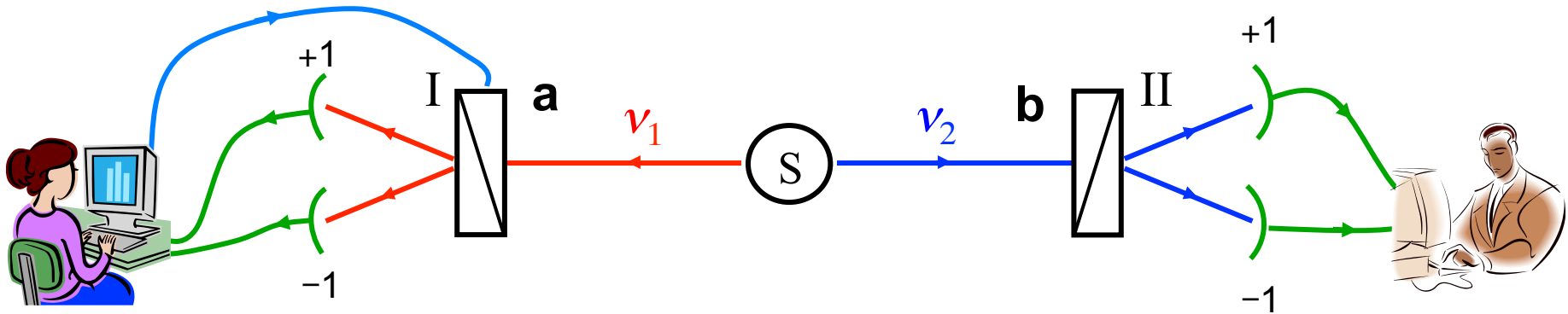
Joint detections: $P_{++}(\mathbf{a},\mathbf{b}) = P_{--}(\mathbf{a},\mathbf{b}) = \dfrac{1}{2}\cos^2(\mathbf{a},\mathbf{b})$ etc.

Instantaneous change ! Faster than light signaling ?

To measure $P_{++}(\mathbf{a},\mathbf{b})$ Bob must compare his results to the results at I: the transmission of these results from I to Bob is done on a classical channel, not faster than light.

cf. role of classical channel in quantum teleportation.

So there is no problem ?

View *a posteriori* onto the experiment:

During the runs, Alice and Bob carefully record the time and result of each measurement.

After completion of the experiment, they meet and compare their data…

… and they find that $P_{++}(\mathbf{a},\mathbf{b})$ had changed instantaneously when Arthur had changed his polarizers orientation…

Non locality still there, but cannot be used for « practical telegraphy »

Is it a real problem ?

« It has not yet become obvious to me that there is no real problem. I cannot define the real problem, therefore I suspect there's no real problem, but I am not sure there is no real problem. So that's why I like to investigate things. »*

R. Feynman: *Simulating Physics with Computers,* Int. Journ. of Theoret. Phys. 21, 467 (1982)**

* This sentence was written about EPR correlations

** A founding paper on quantum computers