EPR paradox,

Bell's theorem

and entanglement at a distance:

Experimental answers.

Contents

EPR original question:
Can QM be considered complete?

EPR paper (1935):
"if QM is complete (and there are no "hidden variables"),
then there cannot be simultaneous reality to non-commuting operators."

EPR paradox, **gedanken experiment** $\longrightarrow$ an argument that QM is not complete

2 separated particles 1 and 2 (previously in interaction):
$\longrightarrow$ momentum and position have simutaneous reality

Others Gedankenexperiments:
Pair of spin ½ particles, in a singlet state,
     analyzed by 2 Stern-Gerlach filters: Bohm (1952)
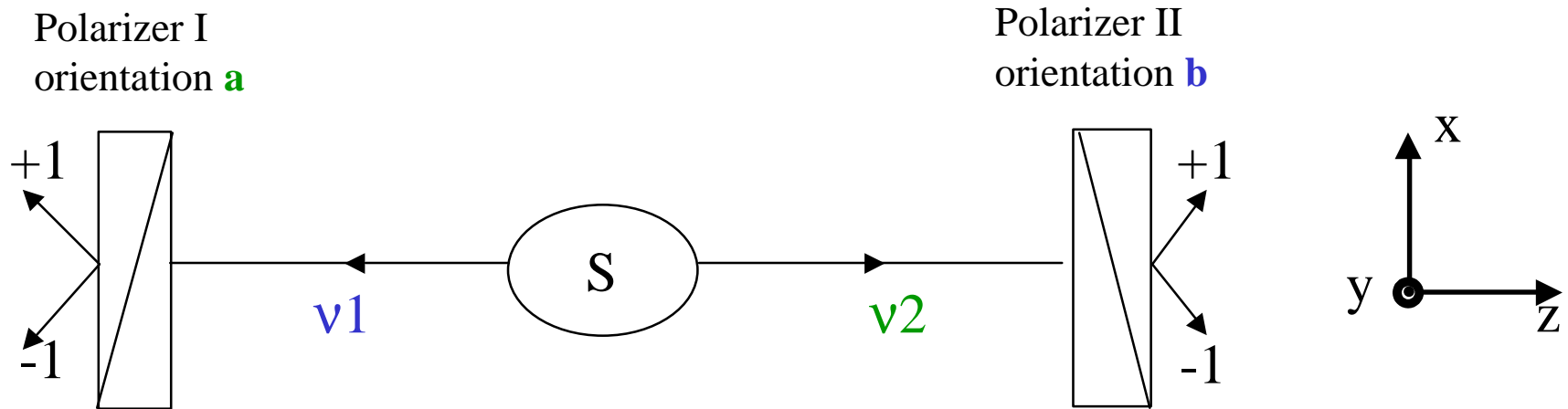
Optical variant: Pair of photons
     measurement of polarization correlation: Bohm and Aharonov (1957)
     $\longrightarrow$ **actual experiment**

EPR « GedankenExperiment »
with photons correlated in polarization

Polarizer I
orientation **a**

Polarizer II
orientation **b**

+1

+1

ν1

S

ν2

x

y

z

-1

-1

Measurement of linear polarization of ν1 : result A(**a**)

Measurement of linear polarization of ν2 : result B(**b**)

= +1 if polariszation // **a** (**b**)

or −1 if polariszation ⊥ **a** (**b**).

$$\left|\psi(1,2)\right\rangle = \frac{1}{\sqrt{2}}\left[\left|x,x\right\rangle + \left|y,y\right\rangle\right]$$ where |x> and |y> are linear polarizations states

This state cannot be factorized into a product of 2 states associated to each photon:

⟶ **entangled state**

EPR « GedankenExperiment »
with photons correlated in polarization

'entangled' quantum states of two particles :

      their global state is perfectly defined

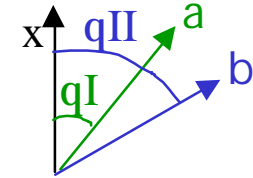   whereas the states of the separate particles remain totally undefined

the information contained in an entangled state

      is all about the correlation between the two particles,

      nothing is said (can be known) about the states of the individual particles.

EPR « GedankenExperiment »
with photons correlated in polarization

Polarizer I (II) measures polarization along a (b).

Probabilities: $P_+(\mathbf{a})$= probability to obtain +1 in I (along **a**)

   $P_{++}(\mathbf{a},\mathbf{b})$= probability to obtain +1 in I (along **a**) **and** +1 in II (along **b**)

Correlation coefficient:

Two random variables $A(\mathbf{a})$ et $B(\mathbf{b})$ are correlated if the average value of their product is different of the product of the average values

$$E(\mathbf{a},\mathbf{b}) = \frac{\overline{A.B} - \overline{A}.\overline{B}}{\left(\overline{A^2}.\overline{B^2}\right)^{1/2}} = \overline{A.B} \quad \text{because} \quad \overline{A^2} = \overline{B^2} = 1 \quad \text{and} \quad \overline{A} = \overline{B} = 0$$

A	B	A.B	P_{AB}
1	1	1	P_{++}
1	-1	-1	P_{+-}
-1	1	-1	P_{-+}
-1	-1	1	P_{--}

$$\overline{A(\mathbf{a}).B(\mathbf{b})} = \sum_{A,B} A(\mathbf{a}).B(\mathbf{b})\, P_{A,B}$$

Then:

$$\boxed{E(\mathbf{a},\mathbf{b}) = \overline{A(\mathbf{a}).B(\mathbf{b})} = P_{++}(\mathbf{a},\mathbf{b}) + P_{--}(\mathbf{a},\mathbf{b}) - P_{-+}(\mathbf{a},\mathbf{b}) - P_{+-}(\mathbf{a},\mathbf{b})}$$
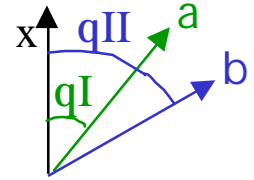
EPR « GedankenExperiment »
with photons correlated in polarization
QM predictions

$$|+\mathbf{a}\rangle = \cos\theta_I|x\rangle + \sin\theta_I|y\rangle \qquad\qquad |+\mathbf{b}\rangle = \cos\theta_{II}|x\rangle + \sin\theta_{II}|y\rangle$$

$$|-\mathbf{a}\rangle = -\sin\theta_I|x\rangle + \cos\theta_I|y\rangle \qquad\qquad |-\mathbf{b}\rangle = -\sin\theta_{II}|x\rangle + \cos\theta_{II}|y\rangle$$

$$P_{++}(\mathbf{a},\mathbf{b}) = \left|\langle +\mathbf{a},+\mathbf{b}\,|\,?1,?2\rangle\right|^2 = \frac{1}{2}\cos^2(\theta_I - \theta_{II}) = \frac{1}{2}\cos^2\theta \qquad |\nu 1,\nu 2\rangle = \frac{1}{\sqrt{2}}\big[|+\mathbf{a},+\mathbf{a}\rangle + |-\mathbf{a},-\mathbf{a}\rangle\big]$$

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

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

$$\boxed{E_{QM}(\mathbf{a},\mathbf{b}) = \cos 2\theta}$$

QM: although each individual measurement gives random results,
these random results are correlated.

If parallel (or perpendicular) orientations of the polarizers I and II
$\longrightarrow$ correlation is total $|E_{QM}|=1$

Bell's inequalities (BI)

Until 1964, debate with QM: philosophical

1964, Bell's theorem:

> ➤provides a quantitative criterion
> to test « reasonably » Local Supplementary Parameters Theories versus QM.

> ➤allows one to give an experimental answer
> to the EPR original question: Can QM be considered complete?

The theorem:
Local Supplementary Parameters Theories are constrained by BI ;

certain predictions of Q M violate BI ,
and therefore Q M is incompatible with Local Supplementary Parameters Theories.

Bell's inequalities
Formalism

Introduction of supplemental (« hidden ») parameters **l**,
not predicted by QM, determine the results of measurements at I and II

2 photons of a given pair : commun properties **l**
l are randomly distributed among pairs
ρ(**l**) distribution of **l** on an ensemble of emitted pairs: $\int_{\Gamma} \rho(\lambda)d\lambda = 1$

Result of the measure of the polarization of ν1 along **a**: A(**l**,**a**)=+1 ou –1
……………………………………………..… ν2 along **b**: B(**l**,**b**)=+1 ou -1

Vital assumptions:

A does not depend on **b**
B …………………………… on **a**
r …………………………… on **a** and **b**.

Correlation function:

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

<u>Additional correlations</u> because both A and B depend on **l**

Bell's inequalities

Main hypotheses for an experiment with photons correlated in polarization:

i)   when both polarizers are along **a:** $E(\mathbf{a},\mathbf{a})=1$ $A(\lambda,\mathbf{a})=B(\lambda,\mathbf{a})$

ii) $|A(\lambda,\mathbf{a})|^2 =1$ $|A(\lambda,\mathbf{a})B(\lambda,\mathbf{b})|=1$ and $|A(\lambda,\mathbf{a})A(\lambda,\mathbf{b})|=1$ because $A,B=\pm1$

$$E(\mathbf{a},\mathbf{b}) - E(\mathbf{a},\mathbf{c}) = \int_{\Gamma} d\lambda \rho(\lambda)\big[A(\lambda,\mathbf{a})B(\lambda,\mathbf{b}) - A(\lambda,\mathbf{a})B(\lambda,\mathbf{c})\big]$$

$$= \int_{\Gamma} d\lambda \rho(\lambda)\big[A(\lambda,\mathbf{a})A(\lambda,\mathbf{b}) - A(\lambda,\mathbf{a})A(\lambda,\mathbf{c})\big]$$

$$= \int_{\Gamma} d\lambda \rho(\lambda)A(\lambda,\mathbf{a})A(\lambda,\mathbf{b})\big[1 - A(\lambda,\mathbf{b})A(\lambda,\mathbf{c})\big]$$

$$\big|E(\mathbf{a},\mathbf{b}) - E(\mathbf{a},\mathbf{c})\big| \leq \int_{G} d\lambda \rho(\lambda)\big|A(\lambda,\mathbf{a})A(\lambda,\mathbf{b})\big|\big[1 - A(\lambda,\mathbf{b})A(\lambda,\mathbf{c})\big]$$

$$\big|E(\mathbf{a},\mathbf{b}) - E(\mathbf{a},\mathbf{c})\big| \leq \int_{G} d\lambda \rho(\lambda)\big[1 - A(\lambda,\mathbf{b})A(\lambda,\mathbf{c})\big] = \int_{G} d\lambda \rho(\lambda)\big[1 - A(\lambda,\mathbf{b})B(\lambda,\mathbf{c})\big]$$

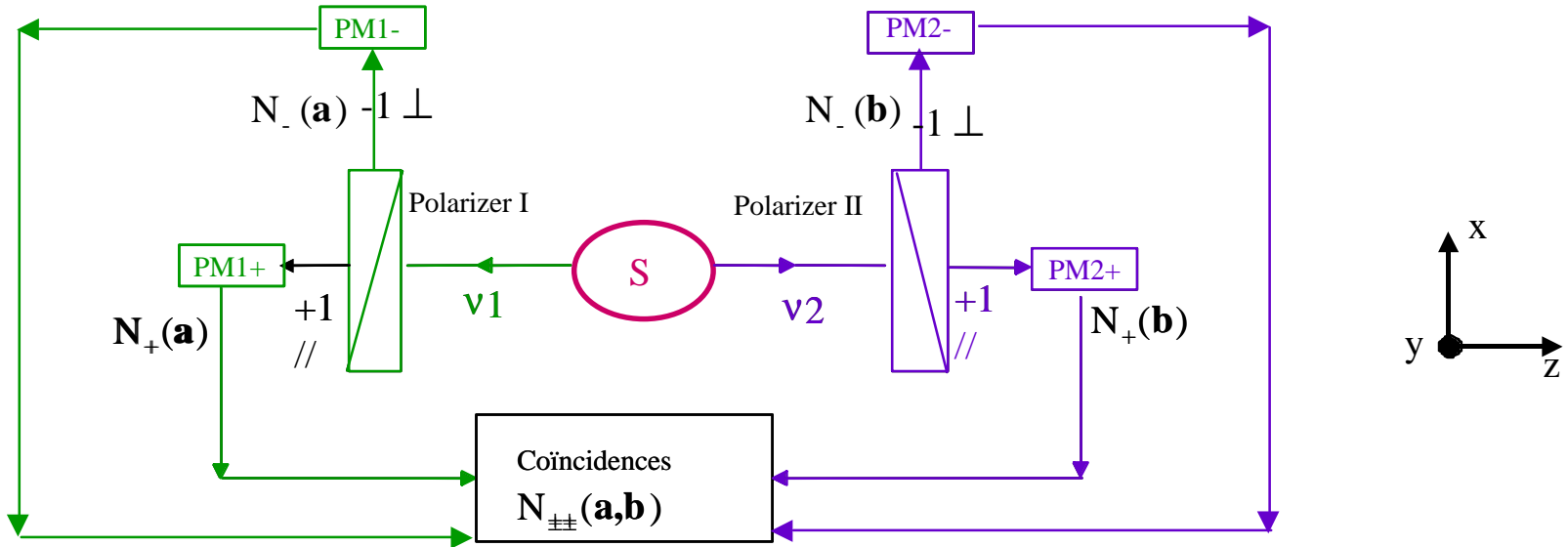$$\boxed{\big|E(\mathbf{a},\mathbf{b}) - E(\mathbf{a},\mathbf{c})\big| \leq 1 - E(\mathbf{b},\mathbf{c})}$$ First formulation of Bell's theorem

Generalized Bell's inequalities
BCHSH (1969)

Directly applicable to experiment.
Two-channels polarizers: separate 2 orthogonal linear polarizations.

$N_\pm$ = counting rate , $N_\pm(\mathbf{a})$ = $P_\pm(\mathbf{a})$ N with N= rate of emission of pairs.
$N_{\pm\pm}$ = coïncidnce rate , $N_{\pm\pm}(\mathbf{a},\mathbf{b})$ = $P_{\pm\pm}(\mathbf{a},\mathbf{b})$ N

$$S = \left| E(\mathbf{a},\mathbf{b}) - E(\mathbf{a},\mathbf{b}') \right| + E(\mathbf{a}',\mathbf{b}) + E(\mathbf{a}',\mathbf{b}')$$

$$-2 \leq S \leq 2$$

Generalized Bell's inequalities

1 channel polarizers

1 channel polarizers   transmit light polarized parallel to **a** (or **b**), but blocks the orthogonal one.
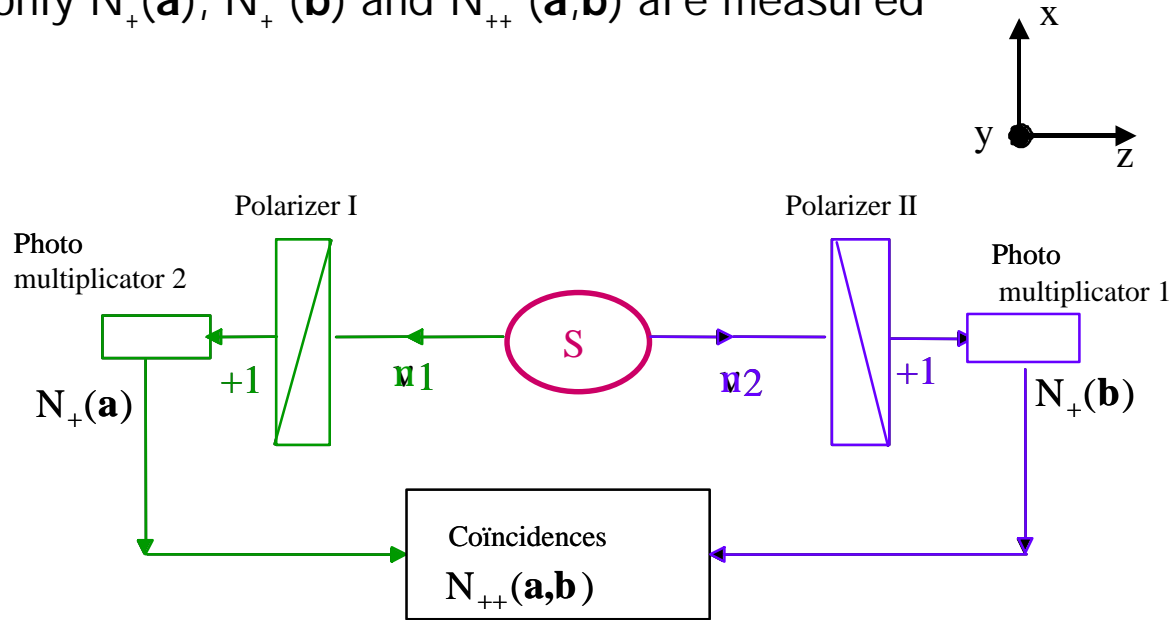
➡ only $N_+(\mathbf{a})$, $N_+(\mathbf{b})$ and $N_{++}(\mathbf{a},\mathbf{b})$ are measured

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

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

N_{--} deduced from N

$$E(\mathbf{a},\mathbf{b}) = \frac{1}{N}(N_{++}(\mathbf{a},\mathbf{b}) + N_{--}(\mathbf{a},\mathbf{b}) - N_{-+}(\mathbf{a},\mathbf{b}) - N_{-+}(\mathbf{a},\mathbf{b})) = 1 - 2\frac{N_+(\mathbf{a}) + N_+(\mathbf{b})}{N} + 4\frac{N_{++}(\mathbf{a},\mathbf{b})}{N}$$

$-1 \leq S' \leq 0$ with

$$S' = \frac{1}{N}\left[N_{++}(\mathbf{a},\mathbf{b}) - N_{++}(\mathbf{a},\mathbf{b}') + N_{++}(\mathbf{a}',\mathbf{b}) + N_{++}(\mathbf{a}',\mathbf{b}') - N_+(\mathbf{a}') - N_+(\mathbf{b}') \right]$$

Generalized Bell's inequalities
1 channel polarizers

Realistic experiments:

Only 10^{-3} of the emitted photons detected $N_+ \approx 10^{-3}$ $N_{++} \approx 10^{-6}$

no possibility of violation of the generalized Bell's inequalities
one needs to consider only the pairs actually detected
➡ measured the rates when polarizers are removed

$N_{++}(\mathbf{a}, \infty) = N_{++}(\mathbf{a},\mathbf{b}) + N_{+-}(\mathbf{a},\mathbf{b})$ polarizer I removed

$N_{++}(\infty, \mathbf{b}) = N_{++}(\mathbf{a},\mathbf{b}) + N_{-+}(\mathbf{a},\mathbf{b})$ polarizer II removed

$N_{++}(\infty, \infty) = N_{++}(\mathbf{a},\mathbf{b}) + N_{+-}(\mathbf{a},\mathbf{b}) + N_{-+}(\mathbf{a},\mathbf{b}) + N_{--}(\mathbf{a},\mathbf{b})$ both polarizers removed

$-1 \leq S' \leq 0$ with

$$S' = \frac{1}{N(\infty,\infty)}\left[N_{++}(\mathbf{a},\mathbf{b}) - N_{++}(\mathbf{a},\mathbf{b}') + N_{++}(\mathbf{a}',\mathbf{b}) + N_{++}(\mathbf{a}',\mathbf{b}') - N_{++}(\mathbf{a}',\infty) - N_{++}(\infty,\mathbf{b})\right]$$

S' depends only on measured quantities of the same order of magnitude

Generalized Bell's inequalities
Conflict with QM

$(\mathbf{a},\mathbf{b})=\theta$, $(\mathbf{b},\mathbf{a'})=\theta'$, $(\mathbf{a'},\mathbf{b'})=\theta''$, $(\mathbf{a},\mathbf{b'})=\theta+\theta'+\theta''$.

$S_{QM}=\cos2\,\theta'+\cos2\,\theta'+\cos2\,\theta''-\cos2\,(\theta+\theta'+\theta'')$

Extrema for $\theta=\theta'=\theta''$:

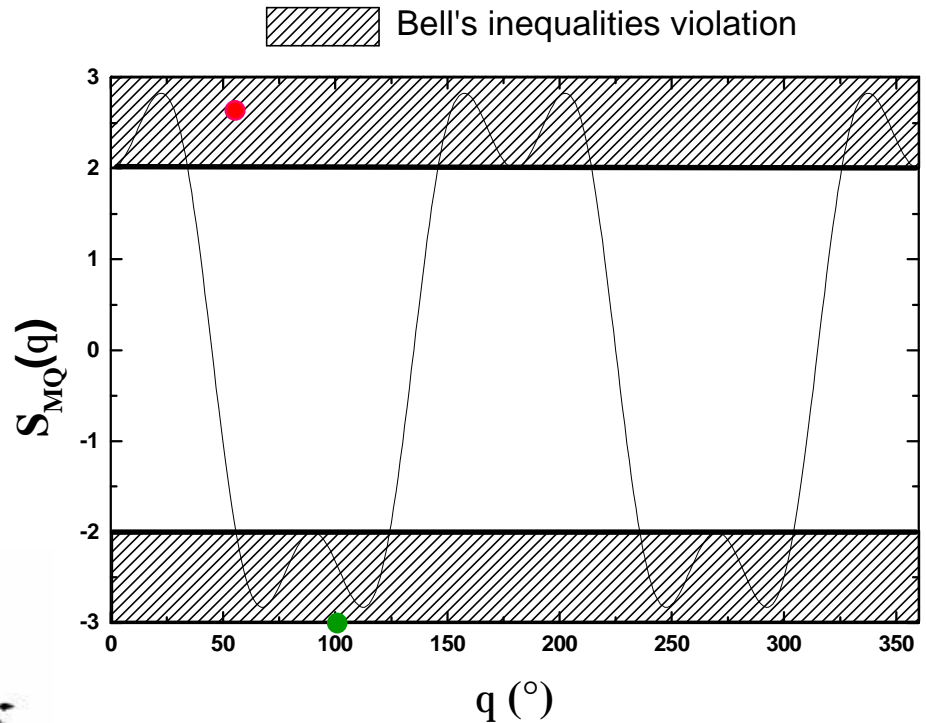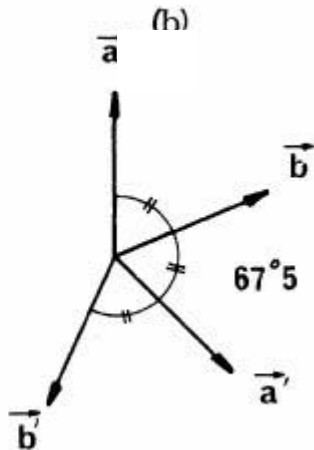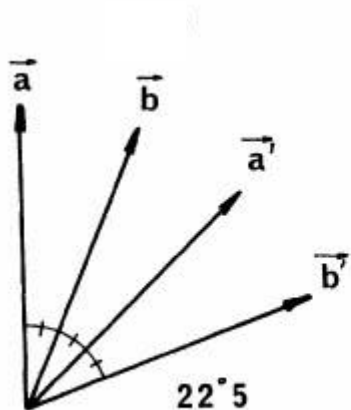$S_{QM}=3\cos2\,\theta-\cos6\,\theta$

$S_{QM}^{max}=2\sqrt{2}$ for $\theta=\pi/8=22.5°$

and

$S_{QM}^{min}=-2\sqrt{2}$ for $\theta=3\pi/8=67.5°$

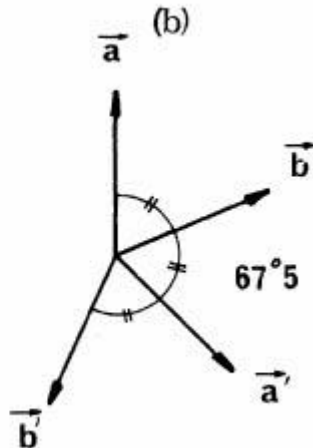➤Maximum violation
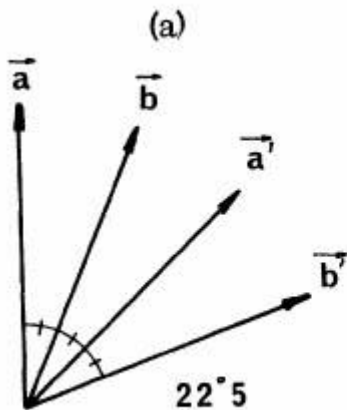
Generalized Bell's inequalities
Conflict with QM

Experiments with 1 channel polarizers

$-1 \leq S' \leq 0$ with

$$S' = \frac{1}{N(\infty, \infty)} \left[N_{++}(\mathbf{a}, \mathbf{b}) - N_{++}(\mathbf{a}, \mathbf{b}') + N_{++}(\mathbf{a}', \mathbf{b}) + N_{++}(\mathbf{a}', \mathbf{b}') - N_{++}(\mathbf{a}', \infty) - N_{++}(\infty, \mathbf{b}) \right]$$

Maximum violation condition: for $\theta = \pi/8 = 22.5°$ and for $\theta = 3\pi/8 = 67.5°$
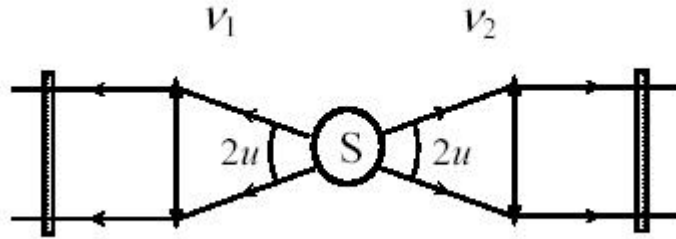

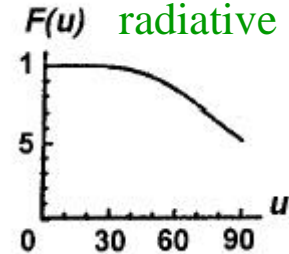$$S'^{max}_{QM} = 0.207 \text{ and } S'^{min}_{QM} = -1.207$$

1 channel polarizers

Realistic experiments:

Not perfect polarizers: rate of transmission : $T_i^{//}$ slitly <1 and $T_i^{\perp}$ close to 0.

Finite solid angle detection 2u: $\qquad E_{QM}(\mathbf{a},\mathbf{b}) = F(u)\cos 2\theta$

for a Ca radiative cascade

QM: $\dfrac{N(\mathbf{a},\mathbf{b})}{N(\infty,\infty)} = \dfrac{1}{4}\left\{ \left(T_1^{//} + T_1^{\perp}\right)\left(T_2^{//} + T_2^{\perp}\right) + F(u)\left(T_1^{//} - T_1^{\perp}\right)\left(T_2^{//} - T_2^{\perp}\right)\cos\left(2\,\mathbf{a}.\mathbf{b}\right)\right\}$

$\dfrac{N(\mathbf{a},\infty)}{N(\infty,\infty)} = \dfrac{1}{2}\left(T_1^{//} + T_1^{\perp}\right) \qquad\qquad \dfrac{N(\mathbf{b},\infty)}{N(\infty,\infty)} = \dfrac{1}{2}\left(T_2^{//} + T_2^{\perp}\right)$

For $\theta = \pi/8$ et $\theta = 3\pi/8$:

For u=30°, $T_1^{//} = T_2^{//} = 0.95$ and $T_1^{\perp} = T_2^{\perp} = 0.05$ $\qquad$ $\boxed{S_{QM}^{'max} = 0.06 \text{ et } S_{QM}^{'min} = -1.06}$

Generalized Bell's inequalities
Conflict with QM

1 channel polarizers: Freedman inequality

N_{QM} depends only on the angle θ between **a** and **b**.

Generalized Bell inequalities
1 channel polarizers
maximum conflict

$$\delta \leq 0 \text{ with } \delta = \frac{N(22.5°) - N(67.5°)}{N(\infty, \infty)} - \frac{1}{4}$$

⚠️ Not only 3 distinct measurements

one has to check that a rotation of both polarizers does not change N

For u=30°, $T_1^{//} = T_2^{//} = 0.95$ and $T_1^{\perp} = T_2^{\perp} = 0.05$ δ_{QM}=0.05

Bell's inequalities

 3 hypotheses:

❖Existence of supplementary parameters
Renders an account of the correlation at a distance

⟶   absolutely necessary to obtain Bell' inequalities conflicting with QM

❖Determinism
Easy to generalize the formalism to Stochastic Supplementatry Parameter Theories
deterministic measurement functions A and B replaced by probalistic functions

Bell's inequalities still hold, conflict does not disapear...

⟶   deterministic character of the formalism not the reason for the conflict

❖Locality
- result of a measurement A with I does not depend on the orientation **b** of I I
 and vice-versa
- the way the pair are emitted by the source does not depend on **a** and **b**.

⟶   crucial assumption: Bell' inequalities will no longer hold without it

From Bell's theorem to a realistic experiment

§ produce pairs of photons in an EPR state,

§ measure the 4 coincidence rates $N_{\pm\pm}$(**a, b)** with detectors in the output channels of the polarizers

➡ E(a,b) for polarizers in orientations **a** and **b**

§ perform 4 measurements of this type in orientations **(a,b)**, **(a,b')**, **(a',b)**, and **(a',b')**

➡ a measured value S_{exp} **(a, a', b, b').**

§ choose a situation where QM predicts that S violates Bell's inequalities,

➡ a test allowing one to discriminate between QM and any local supplementary parameter theory.

§ experiment with variable polarizers,

➡ a test for the more general class of « *separable* » (or *causal* in the relativistic sense) Supplementary Parameters Theories.

From Bell's theorem to a realistic experiment

But:

1) Sensitive situations are rare

       the 2 subsystems must be in a entangled state

       the measured quantities should be not commuting observables

2) experimental inefficiencies (polarizers defects, accidental birefringences...)

    → a decrease of E(a,b)

    → S_{MQ} (**a**,**a′**,**b**,**b′**) is multiplied by a factor less than 1,

       the conflict with Bell's Inequalities decreases, even may vanish.

**The actual experiment must be as close
as possible from the Gedanken experiment**

First experiments in the 70's.

g photons

positronium (1 electron + 1 positron) desintegration: 2 γ photons (0.5MeV)

$$\left|\psi(1,2)\right\rangle = \frac{1}{\sqrt{2}}\left[\left|x,y\right\rangle - \left|y,x\right\rangle\right]$$

Entangled state, good candidate to test Bell inequalities
with a correlation coefficient : $E_{MQ}(a,b) = -\cos 2\theta$

But: No polarizers available for this energy

The polarization is inferred from Compton scattering measurements
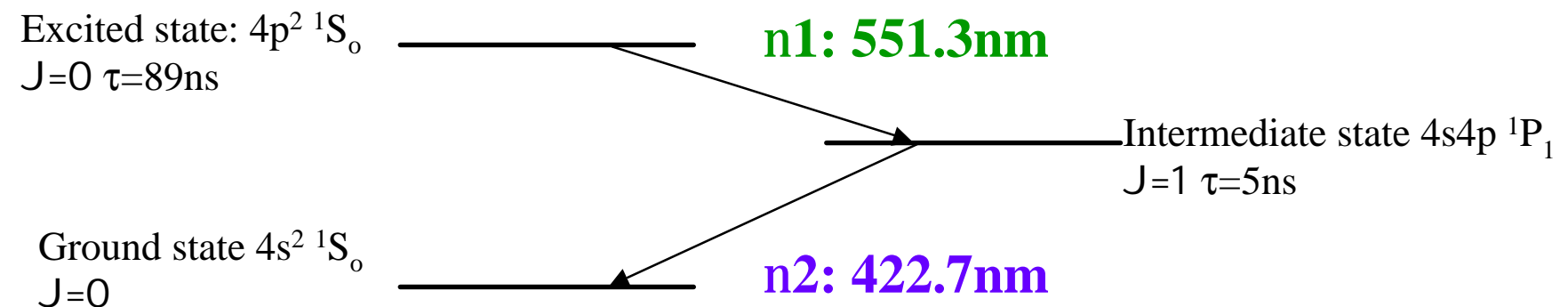by the use of a QM calculation!!!

Agreement with QM but not a test of Bell inequalities!!!!

Nuevo Cim. **25** (1975) 633
J. Phys. **G 2** (1976) 613.

First experiments in the 70's.
visible photons from atomic cascades

Polarizers available for visible photons

0-1-0   Calcium cascade

Excited state: $4p^2 \ {}^1S_o$
J=0 τ=89ns

n1: 551.3nm

Intermediate state $4s4p \ {}^1P_1$
J=1 τ=5ns

Ground state $4s^2 \ {}^1S_o$
J=0

n2: 422.7nm

$4p^2 \ {}^1S_o$ to $4s4p \ {}^1P_1$: $\Delta m_J=\pm 1$
$4s4p \ {}^1P_1$ to $4s^2 \ {}^1S_o$: conservation of J $\longrightarrow$ entangled photon

Solid angles (also hyperfine structure...)
$\longrightarrow$ decrease or even cancellation of the conflict between BI and QM

$$E_{QM}(\mathbf{a},\mathbf{b}) = \mathbf{F}(\mathbf{u})\cos 2\theta$$ 0-1-0 Ca cascade: u=32°: F(u)=0.948

First experiments in the 70's.
visible photons from atomic cascades

1rst generation

✓ Clauser & Freedman (Berkeley, 1972)
   0-1-0 cascade ^{40} **Ca**, 200 hours $d_{QM}=0.051$
                                                $d_{exp.}=0.05 \pm 0.008$ Q. M.

   Non-direct excitation: spurious de-excitations
   The source is not very efficient

✓ Holt & Pipkin (Harvard, 1973)
   1-1-0 cascade ^{200} **Hg**, 200 hours $d_{QM}=0.016$
                                                $d_{exp.}=-0.034$ B. I.

2nd generation (laser excitation)

✓ Fry & Thompson (Texas, 1976)
   1-1-0 cascade ^{200} **Hg**, 80 mn $d_{QM}=0.044$
                                            $d_{exp.}=0.046$ Q. M.

   Improved source of correlated photons:
   Selective excitation of the upper level of the cascade using a laser

single channel polarizers : indirect reasoning, auxiliary calibrations required.

Orsay experiments (1981–1982)
the source of pairs of correlated photon

Aim:
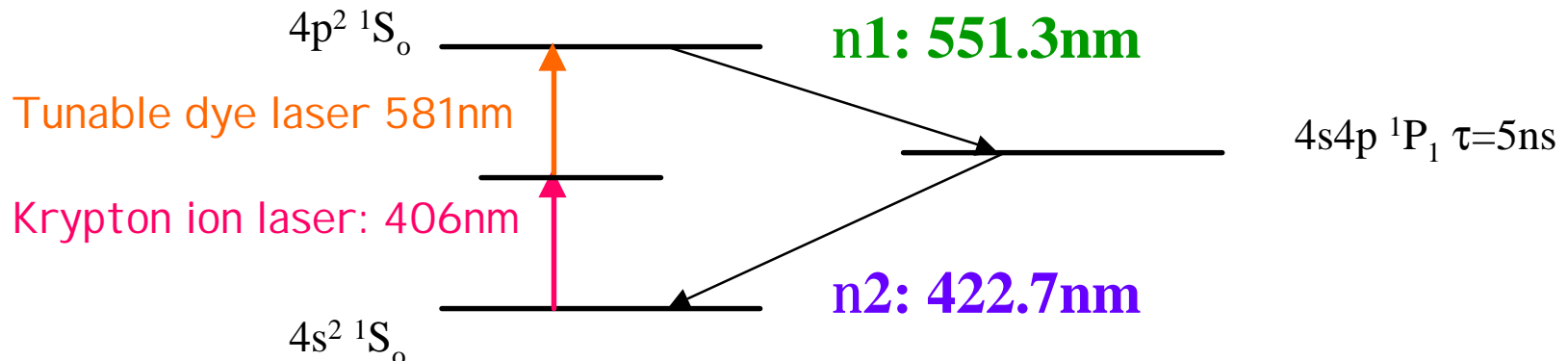develop a high efficiency stable and well controlled source of entangled photons

The source:
2 photons selective excitation of the 0-1-0 cascade of calcium:
lifetime τ of intermediate level short (5ns):

excitation rate of 1/ τ

$\longrightarrow$ optimal signal-to-noise ratio for coïncidence measurements

NEW: direct excitation using two lasers

$4p^2\ ^1S_o$ **ν1: 551.3nm**

Tunable dye laser 581nm

$4s4p\ ^1P_1\ \tau=5ns$

Krypton ion laser: 406nm

ν2: 422.7nm

$4s^2\ ^1S_o$

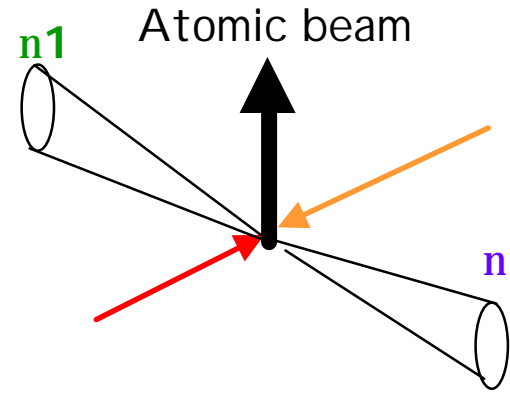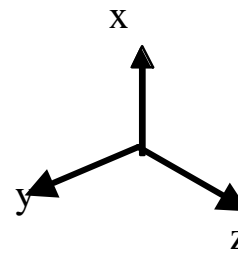**The atom radiative decay delivers ONLY the pair of entangled photons**

Orsay experiments (1981-1982)
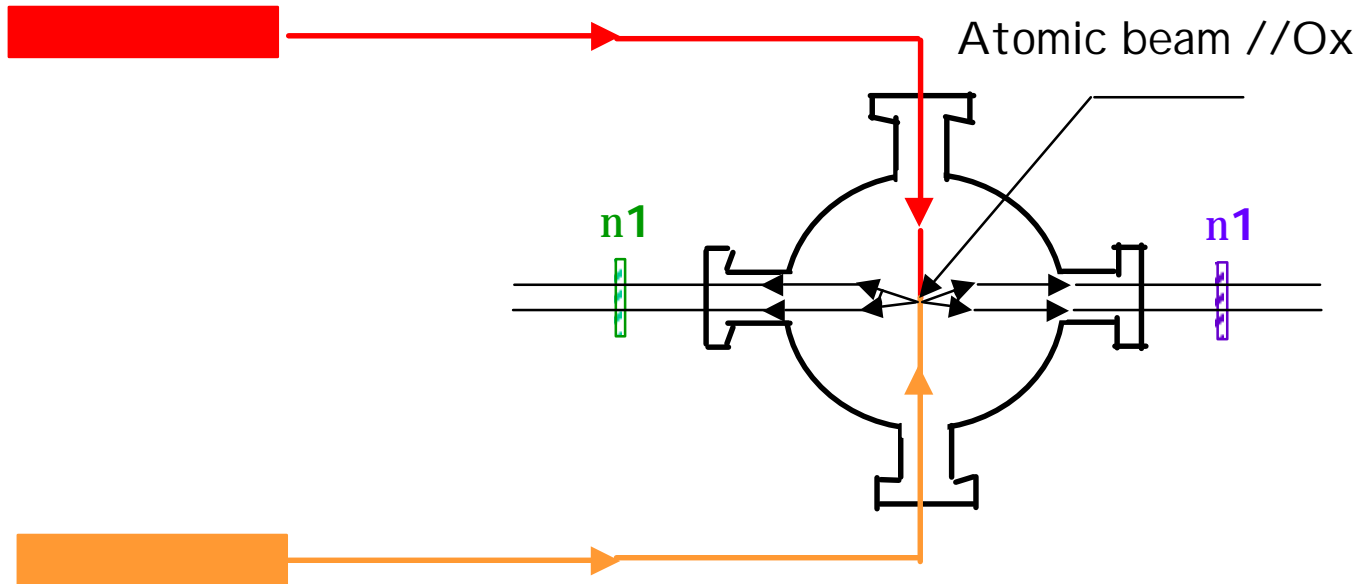## the source of pairs of correlated photon

Atomic radiative cascade
=
Beam of atom emitted by an oven
in a vacuum chamber
+ laser excitation

x

n1

Atomic beam

y

z

n1

Krypton ion laser: 406nm
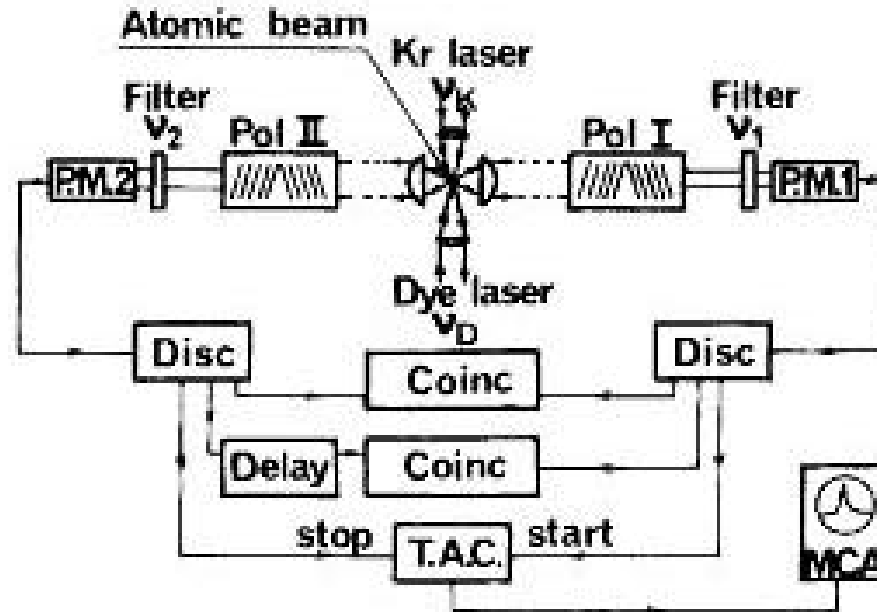
Atomic beam //Ox

n1

n1

y

x

z

Tunable dye laser 581nm

Orsay experiments (1981–1982)
experiments with 1 channel polarizers

Excitation rate more than 10 time larger than that of Fry *et al*

• 1 channel plates polarizers: 10 optical grade glasses plates at Brewster angle

• Photomultipliers: dark rates : 200cts/s

• 2 coïncidence circuits:
      -1 with a 19ns windows monitor N around the null delay
      -1 delayed by 100ns monitored the accidental coïncidences

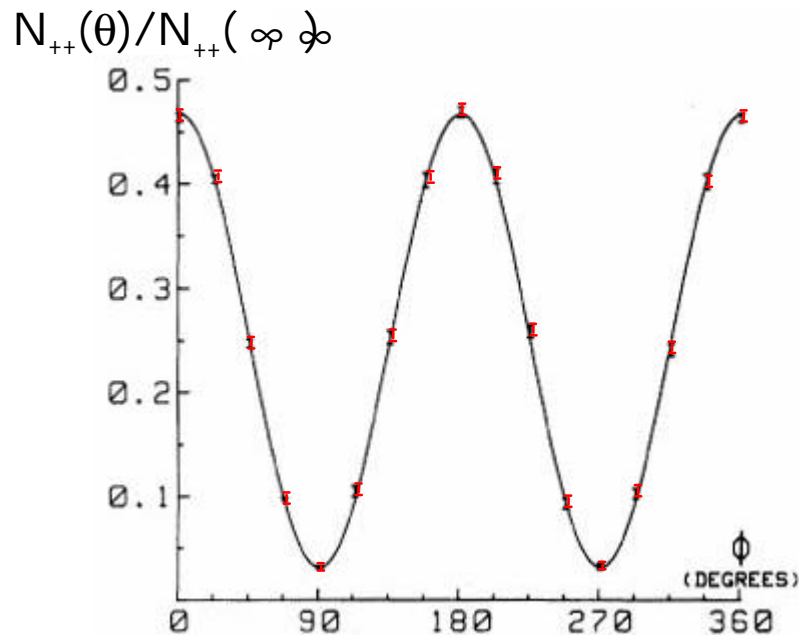**Excellent statistical accuracy in 100 s run**

Orsay experiments (1981-1982)
experiments with 1 channel polarizers

$$u = 32°, T_1^{//} = 0.971, T_2^{//} = 0.968, \ T_1^{\perp} = 0.029, T_2^{\perp} = 0.028$$

Max violation of BI :

d_{QM}=0.0058 ± 0.002
S'_{QM}=0.118 ± 0.005

$d_{exp.}$ =0.00572 ± 0.0043
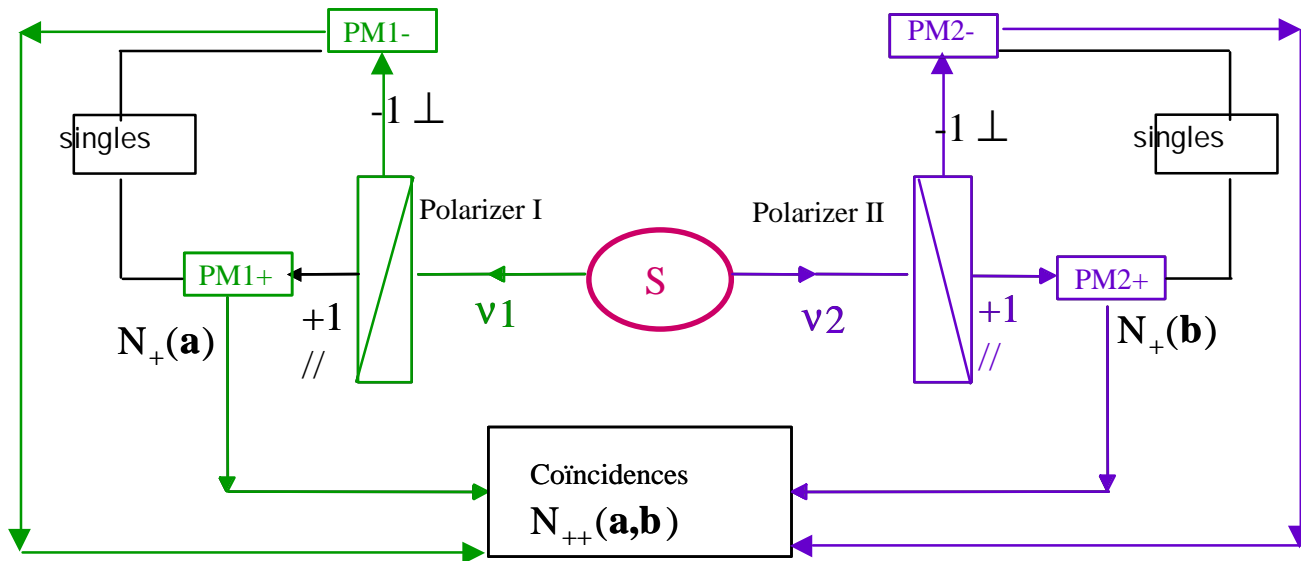$S'_{exp.}$=0.126 ± 0.014

$N_{++}(\theta)/N_{++}(\infty)$

> Excellent agreement with QM.

> Violation of Bell's inequalities by 9σ

> No change in the results with polarizers at a distance (6 m)
larger than the coherence length of ν2 (1.5 m)

Orsay experiments (1981–1982)
experiments with 2 channels polarizers

Following much more closely the ideal Gedankenexperiment

polarizers :   polarizing cubes with dielectric layers

a polarization splitter + corresponding photomultipliers: fixed on a rotatable mount.

Fourfold coïncidence technique:
    measurement of the four coïncidence rates $N\pm\pm(\mathbf{a},\mathbf{b})$ in a single run
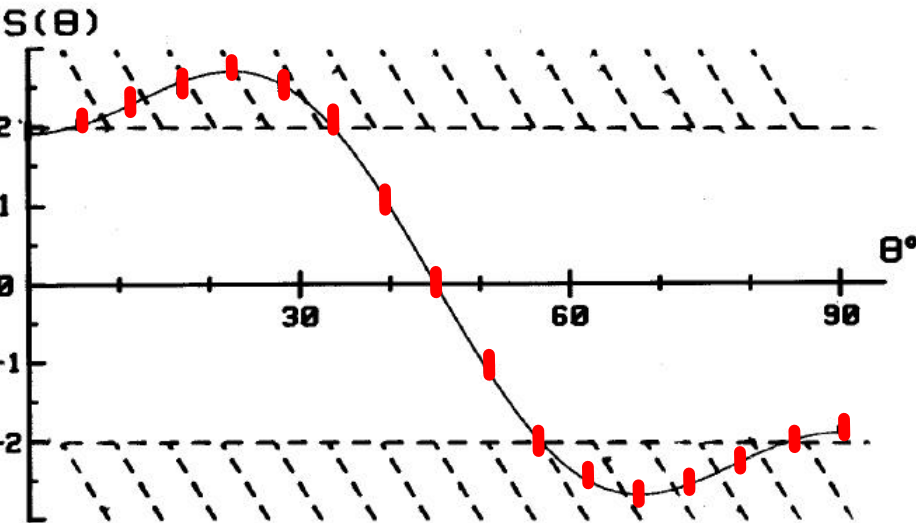
4 measurements: direct test of $-2 \leq S \leq 2$

Orsay experiments (1981–1982)
experiments with 2 channels polarizers

$$u = 32°, T_1^{//} = 0.95, T_2^{//} = 0.93, \ T_1^{\perp} = 0.007, T_2^{\perp} = 0.007$$

Max. violation of BI :

$S_{QM} = 2.7 \pm 0.05$

$S_{exp.} = 2.697 \pm 0.015$

➢Excellent agreement with QM.

➢Violation of Bell's inequalities by 40σ

Orsay experiments (1981–1982)
Timing experiments with optical switches

Static experiment: locality condition=assumption

J. Bell (1964):

« the setting of the instruments are made sufficiently in advance to allow them to reach some mutual rapport by exchange of signals with velocity less than or equal to that of light »

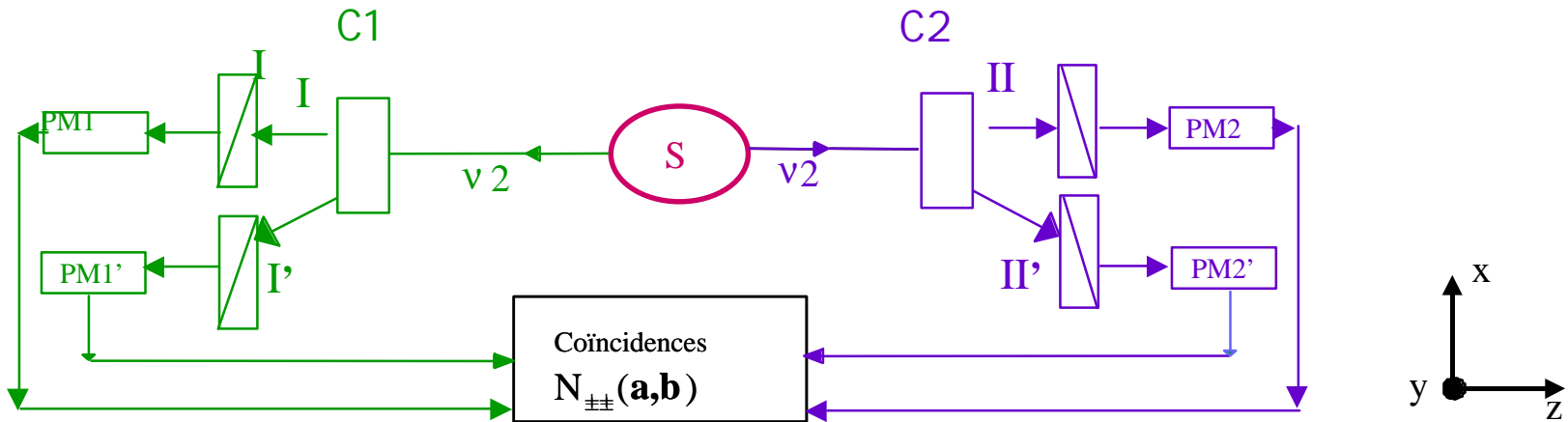⟶ The locality condition no longer hold, nor Bell's inequalities!!!

Importance of experiments
in which the settings are changed during the flight of the particles

⟶ the locality condition=consequence of Einstein's causality
preventing any faster than ligth influence

Orsay experiments (1981–1982)
Timing experiments with optical switches

Time varying analyser= an acousto-optical switch + 2 linear polarizers
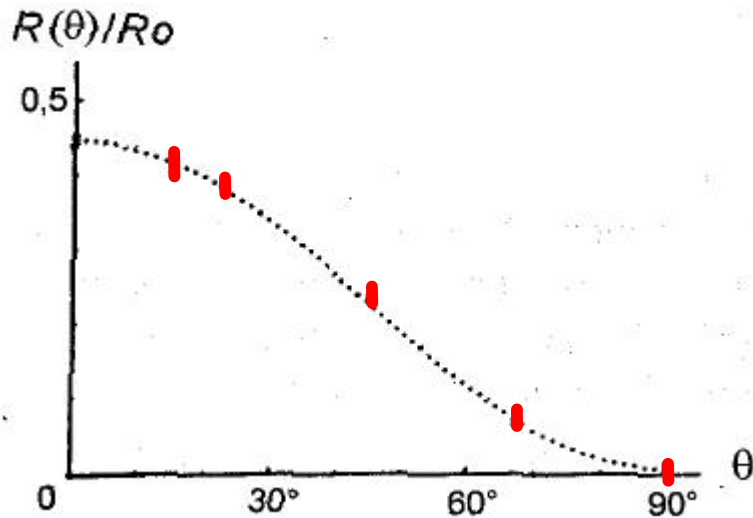(50MHz)

2 switches work at random and are uncorrelated, but periodic

Orsay experiments (1981-1982)
Timing experiments with optical switches

Reduced signal (limited aperture of the switches).
Averaging necessary (15 hours)

Max. violation of BI :

S'_{QM}=0.113 ± 0.005

$S_{exp.}$=0.101 ± 0.02

> Excellent agreement with QM.

> Violation of Bell's inequalities by 5σ

Towards the ideal experiment

2 main loopholes still need to be closed:
- locality loophole
- detection efficiency loophole

Aim of 4th generation experiments:

close this loopholes

- Experiments using a spontaneous parametric down conversion source
  Strong enforcement of the locality condition

- Experiments with massive particles (easier to detect)
 Closure of the detection loopholes

Towards the ideal experiment
4th generation: entangled photons by SPDC

Atomic cascades : photons only weakly correlated in direction
(because of the recoil of the atom)

NEW SOURCES:
A pair of red photons produced by parametric down conversion of a U.V. photon
crossing a non linear medium (frequency splitting of ligth)

$$\overline{\hbar\omega}/2$$

$$\overline{\hbar\omega}$$ Non linear optical crystal $$\overline{\hbar\omega}/2$$
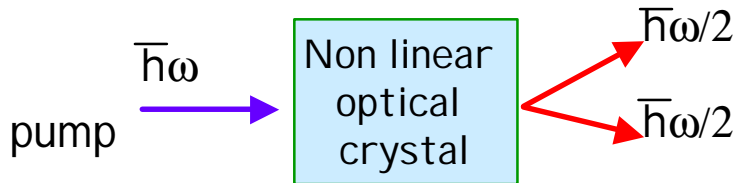
pump

« Parametric »: the state of the crystal is left unchanged in the process

Energy conservation (freq. matching)   of the parent pump photon
Momentum conservation (phase matching)

Type I phase matching: 2 photons $\longrightarrow$ **same** polarizations
Type II phase matching: 2 photons $\longrightarrow$ **perpendicular** polarization

phase matching condition:
determined by the orientation of the crystal axis relative to the pump beam.
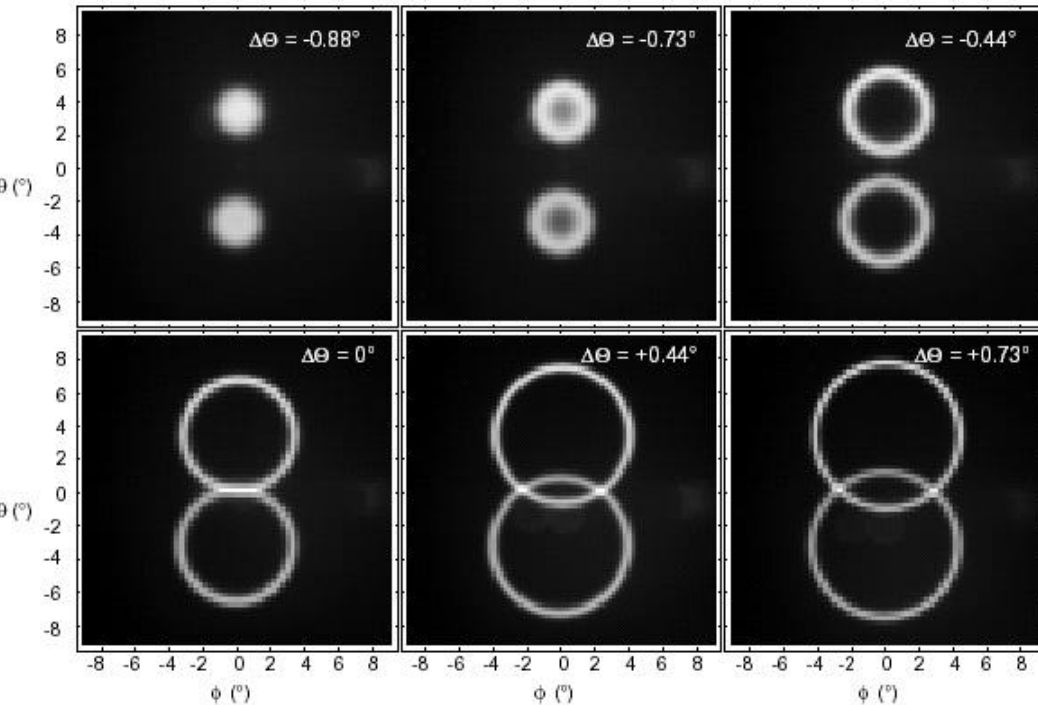
Towards the ideal experiment
4th generation: entangled photons by SPDC

Type II SPDC: the photons are emitted in 2 cones
- given angle between the optic axis of the crystal and the pump

→ entangled polarization state

Phys. Rev. Lett. **75** (1995) 4337

Strong correlation between the direction of emission of the 2 photons
         - larger coïncidence rate (1 order of mag > atomic cascade)
         - narrow photons beams
            → matched with   - optical fibers
                                 - small optical components

<u>Observables</u>: **polarization** but also: **energy and time, position and momentum**

Towards the ideal experiment
4th generation: Energy-time entangled photons

Each photon of the pair is emitted at 2 different times
Relevant observable= time of emission   Conjugate observable: energy

Analyzers= all fiber optical Michelson interferometers

Tapster (1994), Malvern:

Type I SPDC in a cut LI I crystal: 1300nm and 820nm photons

4km optical fibers

Phys. Rev. Lett. **73** (1994) 1923

Tittel (1998), Geneva:

Type I SPDC in a $KNbO_3$ crystal : entangled 1310nm photons

Photons propagating in **10 km** commercial telecommunication fibers

Phys. Rev. Lett. **81** (1998) 3563

**Experimental demonstration of quantum correlations over 10km
Distance does not destroy the "entanglement".**

Towards the ideal experiment
4th generation: improvement of timing experiment

Possible fundamental improvements of the « timing experiment »:

Aspect timing experiment limited by the wide size of the beams:
⟶ impossible to use small electrooptoic devices suitable for random switching

Use of optical fibers:
- small integrated electrooptical devices
- detectors can be kilometers apart

Aspect used sinusoïdal switching, which is predictable in the future

Towards the ideal experiment
4th generation: improvement of timing experiments

Weihs (1998), Innsbrück: Strong enforcement of the locality condition

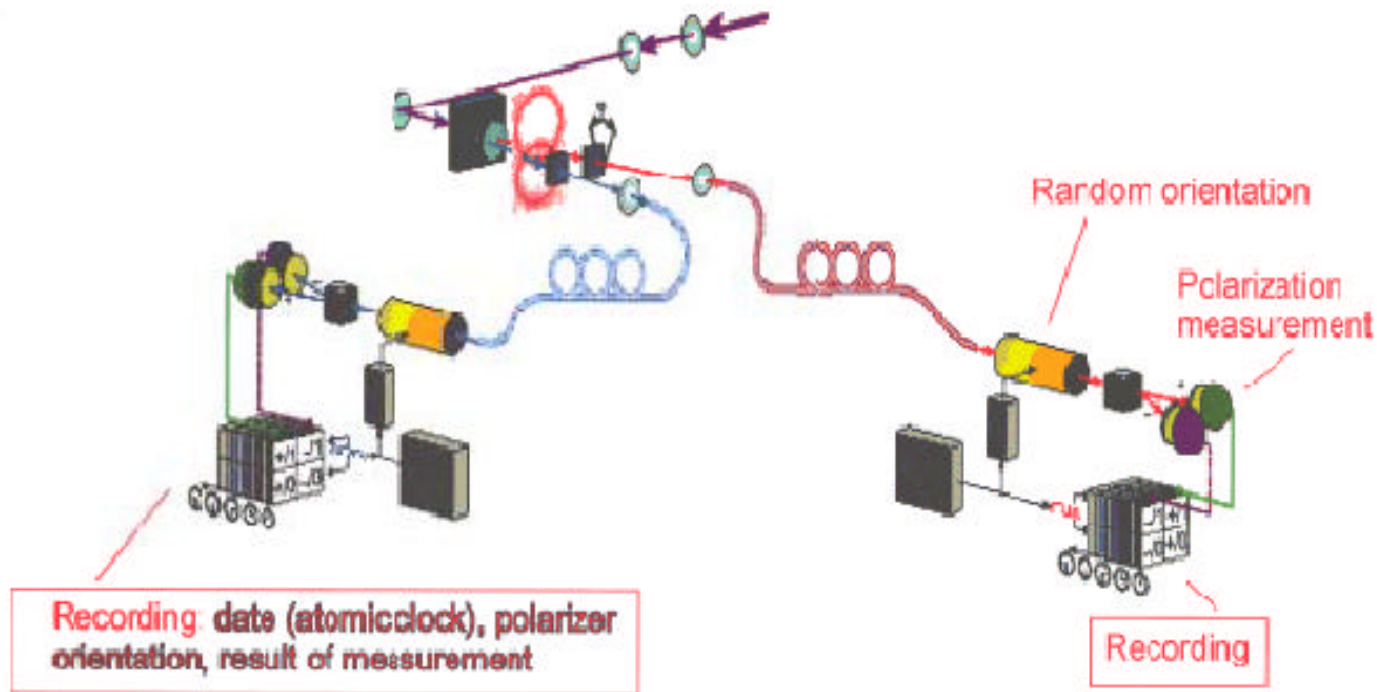Necessary spacelike separation of the observations :

- sufficient physical distance (400m)
- ultra fast and random setting of the polarizers (<1.3µs)
- completely independant data registration
    (use of 2 atomic clocks, comparaison of the data after the experiment)

Pump a BBO crystal with 400mW of 350nm photons from an argon-ion laser.
→ 702nm photons

A telescope narrows the UV pump beam
to enhance the coupling of the red photons into the 2 fibers

Towards the ideal experiment
4th generation: improvement of timing experiment

Random orientation

Polarization measurement

Recording date (atomicclock), polarizer orientation, result of measurement

Recording

Violation of Bell Inequalities by 100σ

Towards the ideal experiment
4th generation:detection loophole

In most experiments:
Only a small fraction of the particles generated are actually detected......

Detection efficiency loophole:
the detected events agree with MQ even if the entire ensemble satisfies BI

"fair sampling assumption" :
the sample of detected pairs is representative of the pairs emitted

Currently available photons detectors:
$\longrightarrow$ too low efficiencies

NEW:
Massive particles: their quantum states are easier to detect

Towards the ideal experiment

4th generation: detection loophole

Experiments with massive particles pairs:

✓ Rydberg atoms and RF photons (ENS Paris 2000)

✓ Trapped ions (Rowe, Boulder, 2001)
   experiments with 100% detection efficiency
   closure of the "detection loophole"
                              but locality loophole not closed!!!!

Ultimate experiment:
   detection loophole closed and locality enforced

200? Still to be done

✓ Sanchez 2004, proposal for a loophole free Bell test
   for photons using homodyne detection

Nature **409** (2001) 791
Phys. Rev. Lett. **93** (2004) 130409

Conclusion

The experimental violation of Bell's inequalities confirms that a pair of entangled photons separated by hundreds of metres must be considered a single non-separable object — it is impossible to assign local physical reality to each photon.

Alain Aspect (1999)

Recognizing the extraordinary character of entanglement:

1) failure of «Einstein local realism »

2) a trigger to quantum information

Quantum cryptography:

Quantum computation:
complexity of a problem dramatically reduced (P. Shore),
thanks to massively parallel computation.

Quantum teleportation.