EPR correlations, Bell’s theorem, and entanglement at a distance: the naive view of an experimentalist

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The first quantum revolution (1900-)

- Conceptual (wave particle duality): understanding matter, radiation
- Technological: transistor (IC), laser: information based society

A new quantum revolution (1964-)

- Quantum mechanics applied to single objects:
  - Microscopic: experiments on single electron, ion, photon, atom: quantum jumps, quantum Monte-Carlo
  - Macro(meso)scopic? Cf. Tony’s talk
- Entanglement recognized as a different extraordinary quantum property (as advocated by Einstein): Bell’s inequalities
- A new technological revolution??? (quantum information)

EPR problem, Bell’s inequalities: the naive view of an experimentalist

- Einstein-Podolsky-Rosen correlations
  The Einstein-Bohr debate
- Bell’s theorem
  From epistemology back to physics
- Experimental tests: a brief review
  Mostly photons, also ions
- Conclusion
  Entanglement: a resource for quantum information
  A real conceptual problem?
EPR original question: Can quantum mechanics be considered complete?

Is it possible (necessary?) to explain the probabilistic character of Quantum Mechanics predictions with underlying supplementary parameters (hidden variables)?

It is suggested by the Einstein-Podolsky-Rosen argument, but denied by Bohr (1935)

Bell’s theorem allows one to give an experimental answer.
Einstein-Podolsky-Rosen Gedanken Experiment
with photons correlated in polarization

Measurements of linear polarization of $\nu_1$ along $a$ and of linear polarization of $\nu_2$ along $b$ : results $+1$ or $-1$

$\Rightarrow$ Probabilities of detection in channels $+1$ or $-1$ of polarizer I and in channels $+1$ or $-1$ of polarizer II (in orientations $a$ and $b$).

EPR situation : entangled state

$$|\Psi(\nu_1, \nu_2)\rangle = \frac{1}{\sqrt{2}}\{ |x, x\rangle + |y, y\rangle \}$$
Einstein-Podolsky-Rosen Gedanken Experiment with photons correlated in polarization

- Photons in the entangled state: \( |\Psi(\nu_1, \nu_2)\rangle = \frac{1}{\sqrt{2}} \{ |x,x\rangle + |y,y\rangle \} \)

- Quantum Mechanics predictions:

  \[
  P_+(a) = P_-(a) = \frac{1}{2}; \quad P_+(b) = P_-(b) = \frac{1}{2}
  \]

  Single results random

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

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

Strong correlations

\[(a,b) = 0 \quad \Rightarrow \quad P_{++} = P_{--} = \frac{1}{2}\]

\[P_{+-} = P_{-+} = 0\]
Einstein-Podolsky-Rosen Gedanken Experiment with photons correlated in polarization

Photons in the EPR entangled state: \( |\Psi(\nu_1, \nu_2)\rangle = \frac{1}{\sqrt{2}} \{|x, x\rangle + |y, y\rangle\} \)

Quantum Mechanics predicts a strong polarization correlation

Correlation coefficient

\[
E(a, b) = P_{++} + P_{--} - P_{+-} - P_{-+}
\]

\[
E_{MQ}(a, b) = \cos 2(a, b) \quad \Rightarrow \quad E_{MQ}(0) = 1 \quad ; \quad E_{MQ}(90) = -1
\]
How to understand the EPR correlations? How to make an image?

• Derive it from the calculation algorithm?

Global (straightforward) calculation:

\[ P_{++}(a, b) = \left| \langle +_a, +_b | \Psi(\nu_1, \nu_2) \rangle \right|^2 \]

Hard to make a picture in real space:

• \( |\Psi(\nu_1, \nu_2)\rangle \) is a global 2-particles wave vector

• calculation done in an abstract space, without direct correspondence in real space
How to understand the EPR correlations?

How to make an image?

2-steps calculation (standard QM)

• 1st step: measure at polarizer I

⇒ result +1 (pol. along a) ⇒ projection of the state vector

or ⇒ \( P_{+a} |\Psi(\nu_1, \nu_2)\rangle = |+_a, +_a\rangle \) Photons polarized along a

⇒ result −1 (pol. perp to a)

⇒ result -1 (pol. perp. to a) ⇒ projection of the state vector

⇒ \( P_{-a} |\Psi(\nu_1, \nu_2)\rangle = |-_a, -_a\rangle \) Photons polarized perp to a

What a picture! Polarization of \( \nu_2 \) instantaneously affected by the result of measurement on \( \nu_1 \) … which is far away.

Can’t we try a less bizarre image?
Classical explanation for correlations between distant results of measurements

- Common property \( \lambda \) of both particles of the same pair
- \( \lambda \) randomly determined in S at the emission time

Simple image, but...

completes the formalism of quantum mechanics:

supplementary parameters \( \lambda \) (« hidden variables »)
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Bell’s formalism

Supplementary parameters $\lambda$ determine the results of measurements at I and II

Supplementary parameters $\lambda$ randomly distributed among pairs

A particular hidden-variables theory gives explicit forms of $A$, $B$, $\rho$, and any probability can be calculated accordingly:

$$P_+(a) = \int d\lambda \rho(\lambda) \left( \frac{A(\lambda, a)}{2} + 1 \right)$$

$$E(a, b) = \int d\lambda \rho(\lambda) A(\lambda, a) B(\lambda, b)$$
Naive example of LHVT

Photons polarized at an angle $\lambda$ from $x$ axis

Rotational invariance

$$\rho(\lambda) = \frac{1}{2\pi}$$

$$A(\lambda, a) = \text{sign}\{\cos 2(\theta_a - \lambda)\}$$

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

$= +1$ if $|\theta - \lambda| \leq \pi / 4$

$$\Rightarrow P_+(a) = P_+(b) = 1/2 \quad \text{etc...}$$

Same predictions as quantum mechanics

$$\Rightarrow E(0) = 1 \quad , \quad E(90) = -1$$
Naive example
Correlation coefficient vs. polarizers angle

Quantum mechanics
Naive LHVT

Not bad for such a simple model!

Wouldn’t it be possible, with a more sophisticated model, to reproduce exactly the Quantum Mechanical predictions?

Bell’s theorem answer: NO
Bell’s theorem

Local Hidden Variable Theories ⇒ Bell’s inequalities

\[-2 \leq S \leq 2\] with \( S = E(a, b) - E(a, b') + E(a', b) + E(a', b') \)

Quantum Mechanics, in orientations \((a, b) = (b, a') = (a', b) = \frac{\pi}{8}\)

\[E_{MQ}(a, b) = \cos 2(a, b)\]

\[S_{QM} = 2\sqrt{2}\]

CONFLICT! The possibility of completing QM with Hidden Variables is no longer a matter of taste. It has become an experimental question.
Hypotheses for Bell’s inequalities
(⇒ conflict with Q. M.)

Hidden variables (supplementary parameters)

or some « classical » explanation – « à la Einstein » – for the EPR correlations, involving physical reality

Locality $A(\lambda, a, b)$ $B(\lambda, a, b)$ $\rho(\lambda, a, b)$

Bell’s inequalities hold for any Local Realist Theory
The locality condition

\[ A(\lambda, a, b) \quad B(\lambda, a, b) \quad \rho(\lambda, a, b) \]

It can be stated as a reasonable assumption, but…

…in an experiment with time-variable analyzers (orientations randomly changed with a period smaller than \(L / c\) with \(L = \) distance between analyzers) the locality condition becomes a consequence of Einstein’s causality (no faster-than-light influences)
Einstein-Podolsky-Rosen Gedankenexperiment with variable polarizers

• Photons in the EPR entangled state:

Quantum Mechanics

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

Bell’s inequalities (Einstein’s local realism)

\[ -2 \leq S \leq 2 \]

\[ S = E(a, b) - E(a, b') + E(a', b) + E(a', b') \]

\[ |\Psi(v_1, v_2)\rangle = \frac{1}{\sqrt{2}} \{ |x, x\rangle + |y, y\rangle \} \]
Bell’s theorem

Some predictions of Quantum Mechanics (in EPR situations) can not be mimicked by a « reasonable classical-like model » in the spirit of Einstein’s ideas.

What about nature ?

When Bell’s theorem appeared, there was no experimental result available for testing Bell’s inequalities vs. Quantum Mechanics.

Couldn’t it be that the violation of Bell’s inequalities indicates a limit of the validity of Quantum Mechanics ?
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First experiments with EPR pairs

Experiments with $\gamma$ photons (0.5 MeV) produced in positronium desintegration

Experiments with protons (proton scattering on a target)

Agreement with QM, but not a test of Bell’s inequalities

There are no polarizers (apparatus with 2 outcome). The polarization is inferred from a Compton scattering, by use of a QM calculation.
Visible photons EPR pairs produced in some atomic radiative cascades

Polarizers do exist for visible photons

EPR pairs produced in radiative cascades \(J = 0 \rightarrow J = 1 \rightarrow J = 0\)

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

Any computable extra effect (finite solid angle, hyperfine structure…) leads to a decrease or even a cancellation of the conflict between Bell’s inequalities and Quantum Mechanics.

The experiment must be as ideal as possible
First experiments with visible photons produced in atomic radiative cascades

1\textsuperscript{st} generation

• Clauser & Freedman (Berkeley, 1972)
  \(^{40}\text{Ca}\) 200 hours M. Q.

• Holt & Pipkin (Harvard, 1973)
  \(^{200}\text{Hg}\) 200 hours B. I.

2\textsuperscript{nd} generation (laser excitation ***)

• Fry & Thompson (Texas A&M, 1976)
  \(^{200}\text{Hg}\) 80 mn M. Q.

In these experiments, single channel polarizers: indirect reasoning, auxiliary calibrations required.
Orsay source of entangled photons

\[ 4p^2 \, ^{1}S_0 - 4s4p \, ^{1}P_1 - 4p^2 \, ^{1}S_0 \]

radiative cascade in calcium 40

Already used in Berkeley experiment

\[ \nu_1 = 551 \text{ nm} \]

\[ \nu_2 = 423 \text{ nm} \]

\[ \tau_r = 5 \text{ ns} \]

New: 2 photon laser excitation

⇒ Selective excitation (isotope, level)
⇒ Small source: 0.5 x 0.05 mm\(^2\)
⇒ Optimum cascade rate (4 x 10\(^7\) s\(^{-1}\)) easily achieved

1% accuracy on coincidence rate in 100 s
The Orsay source of entangled photons
Experiment with 1-channel polarizers

AA, P. Grangier, G. Roger, PRL 1981

High grade pile of plates polarizers, but only one channel (+1)

- Excellent agreement with QM.
- Violation of Bell’s inequalities by 9 $\sigma$
- No change in the results with polarizers at a distance (6 m) larger than the coherence length of $\nu_2$ (1.5 m)
Experiment with 2- channels polarizers

AA, P. Grangier, G. Roger, PRL 1982

Fourfold coincidence system: the 4 coincidence rates are measured during the same run ⇒ coefficient of correlation

\[
E(a, b) = \frac{N_{++}(a, b) - N_{+-}(a, b) - N_{-+}(a, b) + N_{--}(a, b)}{N_{++}(a, b) + N_{+-}(a, b) + N_{-+}(a, b) + N_{--}(a, b)}
\]
Experiment with 2- channels polarizers

For $\theta = (a, b) = (b, a') = (a', b) = \frac{\pi}{8}$, $S_{\text{exp}}(\theta) = 2.697 \pm 0.015$

Violates Bell’s inequality ($S \leq 2$) by $> 40 \sigma$

No auxiliary calibration necessary.
Excellent agreement with Q.M. $S_{\text{QM}} = 2.70$
Experiment with optical switches
AA, J. Dalibard, G. Roger, PRL 1981

Each switch redirects the photon towards one of two polarizers in different orientations: equivalent to a single polarizer rapidly rotated from an orientation to the other one.

Switching period: 10 ns \(<<\) \(C_1C_2/c = 40\) ns

Spacelike separated events
Experiment with optical switches

In the 1982 Orsay experiment, each switch $C_1$ and $C_2$ worked in a quasi-periodic way, not truly random.

But the two switches were driven by two different generators, drifting independently.
Experiment with optical switches: results

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

Violation of the relevant Bell’s inequality
\( \delta \leq 0 \)
\( \delta_{\text{exp}} = 0.064 \pm 0.01 \)

Good agreement with QM:
\( \delta_{\text{QM}} = 0.059 \)
Towards the ideal experiment

- Perrie et al. (1985): pair of UV photons (metastable deuterium desexcitation)

- **4th generation**: entangled photons by parametric splitting

\[ \hbar \omega \]
\[ \frac{\hbar \omega}{2} \]

- **Alley, Mandel, Rarity, Martiensen, Kimble, Gisin, Zeilinger** (super source by Kwiat, Weinfurter et al.)

- **Perfect correlation**: violation of BI by 100 \( \sigma \) (Innsbruck 1998)

- **Other observables**: time / energy; position / momentum

- **Use of optical fibers**

  \[ \Rightarrow \text{large distances (Malvern, Geneva)} \]

  \[ \Rightarrow \text{experiments with active random polarizers (Innsbruck 1998)} \]

  **Strong enforcement of the locality condition**
Geneva experiment

Use of optical fibers of the commercial telecom network

Non locality at more than 10 km…
Innsbruck experiment

Experiment with randomly reoriented polarizers

Strong violation of Bell’s inequalities, agreement with QM
Towards the ideal experiment

• 4th generation bis: massive particles pairs

  • Rydberg atoms and RF photons (ENS Paris 2000)
  • Trapped ions (Boulder, 2000)

⇒ experiments with 100% detection efficiency
closure of the “detection loophole”

Ultimate experiment: detection loophole closed and locality enforced

200? Still to be done
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Violation of Bell’s inequalities

- **Entanglement demonstrated** \(\Rightarrow\) **quantum information**
  quantum cryptography, quantum computing

- Failure of local realism \(\text{à la} \) Einstein

- Accept negative probabilities (???)

- Is it a real problem?
Recognizing the extraordinary character of entanglement: a trigger to quantum information

Different physical principles (quantum vs. classical) allow different implementations of information processing:

Information is physical (Rolf Landauer)

Quantum cryptography: distribution of a key between two partners. The very principles of quantum mechanics allow one to be sure that there was no eavesdropping (measurement leaves a « footprint »: Bennet-Brassard 84, Ekert 91)

Quantum computation: complexity of a problem dramatically reduced (P. Shore), thanks to massively parallel computation. The phase space for N entangled Qubits has a dimension $2^N$. 
Violation of Bell’s inequalities

• Entanglement demonstrated ⇒ quantum information
  quantum cryptography, quantum computing

• Failure of local realism à la Einstein

• Accept negative probabilities (???)

• Is it a real problem?
Violation of Bell’s inequalities

- Failure of local realism à la Einstein:

« - 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 $S_2$ »

(A. Einstein)

We may have non locality, but it does not allow faster than light signaling!
No faster than light signaling with EPR entangled pairs

Arthur changes the setting of polarizer I from a to a’: can Beatrice instantaneously observe a change on its measurements at II?

Single detections: \( P_+(b) = P_-(b) = 1/2 \)  
No information about a

Joint detections: \( P_{++}(a,b) = P_{--}(a,b) = \frac{1}{2} \cos^2(a,b) \)  
Instantaneous change!

Faster than light signaling?
No faster than light signaling with EPR entangled pairs

Arthur changes the setting of polarizer I from \( a \) to \( a' \): can Beatrice instantaneously observe a change on its measurements at II?

Joint detections:

\[
P_{++}(a, b) = P_{--}(a, b) = \frac{1}{2} \cos^2(a, b) \quad \text{etc.}
\]

Instantaneous change! Faster than light signaling?

To measure \( P_{++}(a, b) \) Beatrice must compare her results to the results at I: the transmission of these results from I to Beatrice 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, Arthur and Beatrice carefully record the time and result of each measurement.

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

... and they find that $P_{++}(a,b)$ 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

Int. Journ. of Theoret. Phys. 21, 467 (1982)