Quantum entanglement in the lab : an experimental training platform for the second quantum revolution

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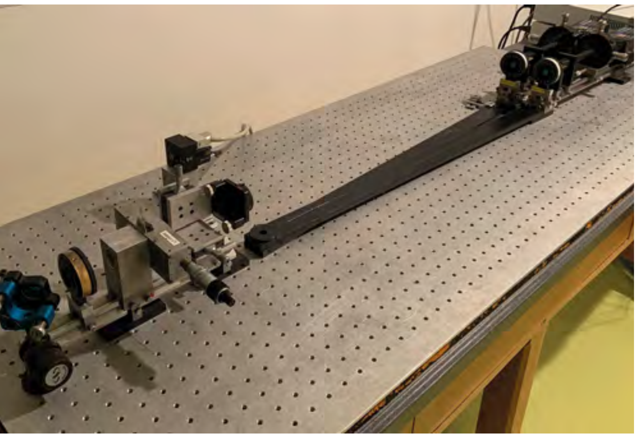

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The recent and rapid progress in the field of quantum technologies stimulates developments of specific courses and experimental training for future engineers and scientists. We describe below the experimental setup developed at Institut d'Optique Graduate School for engineering and Master students. During a labwork session afternoon, students can study a source of polarization entangled state pairs of photons and perform an experimental violation of Bell's inequalities. This emblematic experiment is one of the experiments dedicated to quantum photonics. It was built in 2005 in the LEnsE (the Laboratoire d'Enseignement Experimental) of the *Institut d'Optique Graduate School* and has been perfectly working for almost eighteen years already.

Entangled states represent one of the most strikingly counter-intuitive features of quantum mechanics, and as such, are often held as a great example of what quantum world means. Before the experiments by Alain Aspect and his team at Institut d'Optique reporting Bell's inequalities violation in the early 80s [1], decades of research have led to tremendous results revolutionizing our understanding of light-matter interaction. The first revolution of quantum physics has deep connections with the wave-particle-duality and the description of physical systems using the concept of wave functions. For instance, the process of carrier photogeneration by semiconducting devices is a direct consequence of the ability of quantum mechanics to explain the structure of matter and the optical properties of materials. As a consequence, it is reasonable to consider that many experimental labwork sessions in the LEnsE, dedicated to cameras and light detectors, are true quantum experiments!

However, the term "quantum photonics" usually refers to the concepts that emerged and were popularized after a second quantum revolution. Starting from the Aspect experiments, this second quantum revolution is focused on the most surprising and counter-intuitive predictions of quantum mechanics whose manipulation can lead to the development of a new generation of sensors, quantum communication schemes, simulators or quantum computing.

A two-photon polarization entangled state

Entangled states are a class of multi-particle states whose existence is predicted by quantum mechanics [2,3]. The state of the polarization entangled pairs of photons that we produce in the labwork experiment can be written as:

$$|\psi_{2ph}\rangle = \frac{1}{\sqrt{2}}\left(|V_I\rangle|V_{II}\rangle + |H_I\rangle|H_{II}\rangle\right)$$

This is a typical polarization entangled state where V and H refer to the vertical and horizontal direction of polarization and I and II refer to each photon of the pair.

Why this entangled polarization state is so extraordinary? So strikingly counter-intuitive?

To explore more in details the features exhibited by this two-photon entangled state in polarization, we will perform measurements on the polarization of each photon of the pair. Figure 1 below describes the classical polarization measurement setup that we use in our experiment.

For the entangled state $|\psi_{2ph}\rangle$, whatever the direction of polarization, α, photon I is detected 50% of the time in state $|V_I^\alpha\rangle$ and is detected 50% of the time in state $|H_I^\alpha\rangle$ (the probabilities are : $P(|V_I^\alpha\rangle) = P(|H_I^\alpha\rangle) = 1/2$). The same result would be obtained for photon II ($P\left(|V_I^\beta\rangle\right) = P\left(|H_I^\beta\rangle\right) = 1/2$, whatever the direction of projection β is). So, in this entangled state, none of the photons of the pair has initially a defined polarization state and the measurement process attributes randomly the state $|V_I^\alpha\rangle$ or $|H_I^\alpha\rangle$ to the photon I.

A question now arises: what does happen with the other photon of the pair, let us say photon II? The answer is hard to believe: it is not even necessary to measure the state of photon II! Quantum formalism tells us that the polarization state of photon II is identical to the polarization state already measured of photon I. In other words, if the same settings are selected for both channels ($\beta = \alpha$), the second photon is systematically detected in the same state as photon I. The measurement outcomes on both channels I and II are *perfectly correlated*: that is, the conditional probabilities $P(V_{II}^\alpha|V_I^\alpha)$ and $P(H_{II}^\alpha|H_I^\alpha)$ are equal to 1 whatever α is.

So $P(|V_I^\alpha\rangle,\ |H_{II}^\alpha\rangle) = P(|V_I^\alpha\rangle|V_{II}^\alpha\rangle) = 1/2$
and $P(|H_I^\alpha\rangle,\ |V_{II}^\alpha\rangle) = P(|V_I^\alpha\rangle|H_{II}^\alpha\rangle) = 0$

and the degree of correlation of measurements between both channels is in this case : $E = (\alpha, \alpha) = P(|V_I^\alpha\rangle,\ |V_{II}^\alpha\rangle) + P(|H_I^\alpha\rangle,\ |H_{II}^\alpha\rangle) - P(|H_I^\alpha\rangle,\ |V_{II}^\alpha\rangle) - P(|V_I^\alpha\rangle,\ |H_{II}^\alpha\rangle) = 1$

Bell's parameter

More generally, we can choose to rotate the measurement basis on path I with an angle α and on path II by an angle β, different from α. Quantum formalism then predicts that the conditional probability of detection is expressed as:

$$P\left(|V_I^\alpha\rangle\ \middle|\ |V_{II}^\beta\rangle\right) = \cos^2(\alpha - \beta)$$

which is maximal and equal to 1, as we already noticed, as long as $\alpha = \beta$. The degree of correlation of the measurements between both channels is in this case :

$$\mathrm{E}(\alpha, \beta) = P\left(|V_I^\alpha\rangle, |V_{II}^\beta\rangle\right) + P\left(|H_I^\alpha\rangle, |H_{II}^\beta\rangle\right) - P\left(|H_I^\alpha\rangle, |V_{II}^\beta\rangle\right) - P\left(|V_I^\alpha\rangle, |H_{II}^\beta\rangle\right)$$

$$\mathrm{E}(\alpha, \beta) = cos^2(\alpha, \beta) - sin^2(\alpha, \beta) = \frac{1}{2} cos\, 2(\alpha, \beta)$$

So, with this experiment setup, we can measure the Bell's parameter which is :

$$S_{\mathrm{Bell}} = E(\alpha, \beta) + E(\alpha', \beta) + E(\alpha', \beta') + E(\alpha, \beta')$$

The maximal value is obtained for $\alpha = 22.5°$, $\alpha' = 45°$, $\beta = 45°$ and $\beta' = 67.5°$ for which the Bell's parameter is $S_{\mathrm{Bell}} = 2\sqrt{2}$.

Non-locality in quantum correlations

We must however stress that the formalism of quantum mechanics has several counterintuitive (maybe ●●●

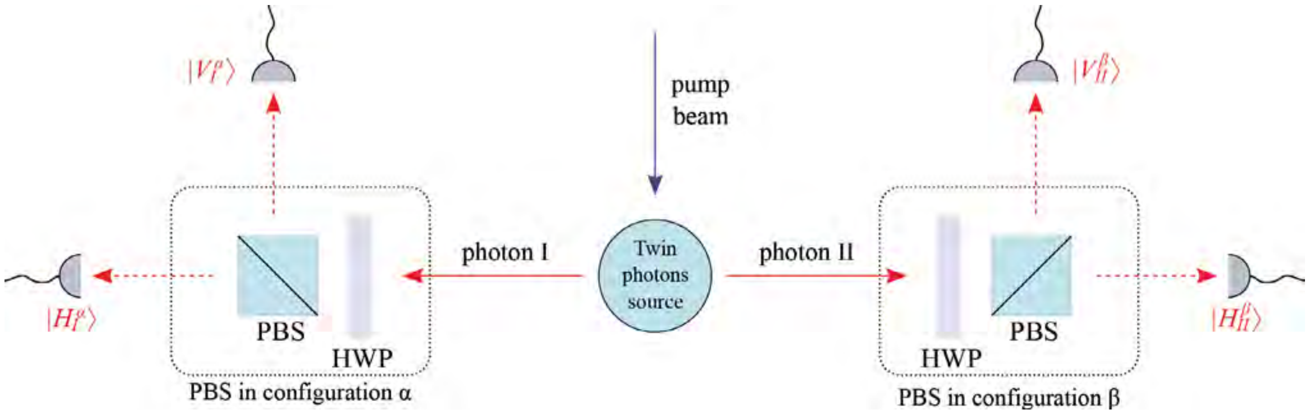


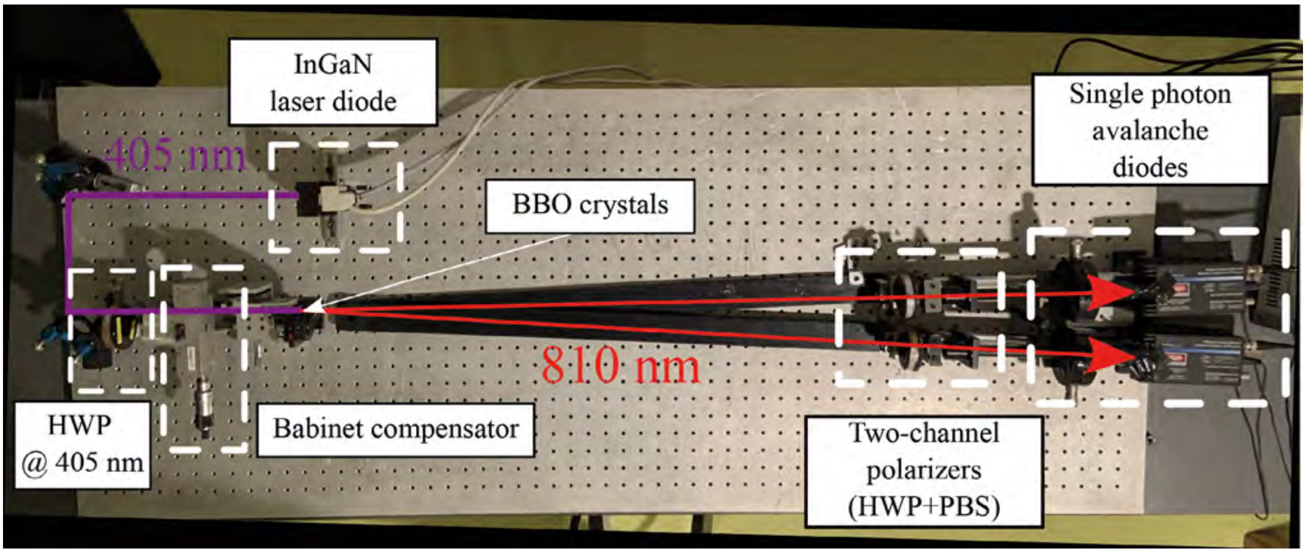
Figure 1. Classical polarization measurement setup: Each channel is composed of a polarizing beam splitter (PBS) preceded by a half-wave plate (HWP) which allows one to choose the projection basis of the polarization measurements (*α* and *β*).

even disturbing!) consequences. Let us recall that the measurement outcomes on photon I are uniformly distributed over states $|V_I^\alpha\rangle$ and $|H_I^\alpha\rangle$, and that this property does not even depend on *α*. So, when considering the outcome of the first measurement occurring in the setup, one cannot assign any preferred direction to any photon whatsoever. The polarizer settings on both channels can be changed independently until the very last moment. Then, as soon as projection occurred on photon *I*, quantum formalism tells us that the state of photon *II* is also instantaneously projected and known with certainty. There is no need to explicitly perform a measurement on photon *II*: it becomes assigned to a specific state, not defined by a measurement of one of its own features, but via a measurement performed on another particle, *possibly located at the opposite side of the universe*! This instantaneous "spooky action at a distance" disrupts our understanding of "locality".

EPR paradox: The completeness of quantum mechanics in question

Entangled states display correlations that seem to involve non-local influence between physically separated, non-interacting systems. This deeply troubled many physicists including Einstein, and led to the famous Einstein-Podolsky-Rosen (EPR) paper published in 1935 [4]. In this article, the authors imagined a similar situation as the one exemplified above in a famous thought experiment ("Gedankenexperiment"). But they also explicitly assumed that such spooky action at a distance was impossible, so that the quantum

Figure 2. Experimental setup built in the LEnsE in 2005



> It seems that Niels Bohr was deeply troubled by the EPR argument relying precisely on quantum formalism itself to show its incompleteness. He was convinced that if the “EPR” reasoning on reality and locality was correct, all of quantum physics would collapse.

physics description failed at giving an appropriate understanding of the process. Einstein and his partners however believed that another theory, compatible with local reality (so called hidden variable theory or HVT), could explain the correlations of entangled states as predicted by quantum mechanics. This theory was yet to establish. The general idea behind local hidden variable theories is the following. It is assumed that the photon pairs have a new kind of physical property: for instance here, an identical "polarization property", shared by both photons and attributed to them via the pair-generation process, and labeled, say, by θ. Since θ is the same for both photons, it would explain why both photons of any pair are measured along the same direction whatever this direction is. And since it is established *at the source*, it is *local*: the photons carry θ with them at all time. The result of the measurement performed on each channel depends on the value of θ for the photon itself, and not on what happens to the other photon. θ is called a *hidden variable*, in the sense that it does not appear explicitly in the expression of the state, $|\psi_{2ph}\rangle$, in the quantum formalism. This tends to show that the wavefunction somehow “lacks” some of the information on the system. This is why it is said that the EPR paper and the hidden variable theories contradict the completeness of the quantum theory.

It seems that Niels Bohr was deeply troubled by the EPR argument relying precisely on quantum formalism itself to show its incompleteness. He was convinced that if the “EPR” reasoning on reality and locality was correct, the whole quantum physics theory would collapse. Bohr defended the formalism of quantum mechanics by asserting that, for these entangled quantum states of several particles, one could not speak of the individual properties of each of the particles: thus, there are no hidden variables. Entangled particles definitely behave as a single object regardless of their separation distance.

The debate between Bohr and Einstein lasted for more than twenty years until they both died. In fact, Einstein never contested the correctness of quantum physics predictions, but how quantum physics explained these predictions.

Bell’s theorem and parameter

But in 1965, surprising breakthrough, the Irish physicist John Bell showed that this debate could be settled experimentally [5]. He showed that if we measure the Bell’s parameter, S_{Bell}, as defined before, assuming any local hidden variable hypothesis, its value is less than two.

$$-2 < S_{\text{Bell}} < 2$$

These are the so-called Bell’s inequalities. In parallel, quantum physics predicts value of $S_{\text{Bell}} > 2$ for specific choices of α, α', β and β' , with a maximal value of $S_{\text{Bell}} = 2\sqrt{2}$. Entangled states are said to violate Bell’s inequalities.

Since the two formalisms are not compatible, then who is right? Einstein or Bohr? An experimental test of Bell’s inequalities is thus to choose a conflictual set of measurements and to measure what is the value of Bell’s parameter, and see if it is compatible or not with a local hidden variable theory.

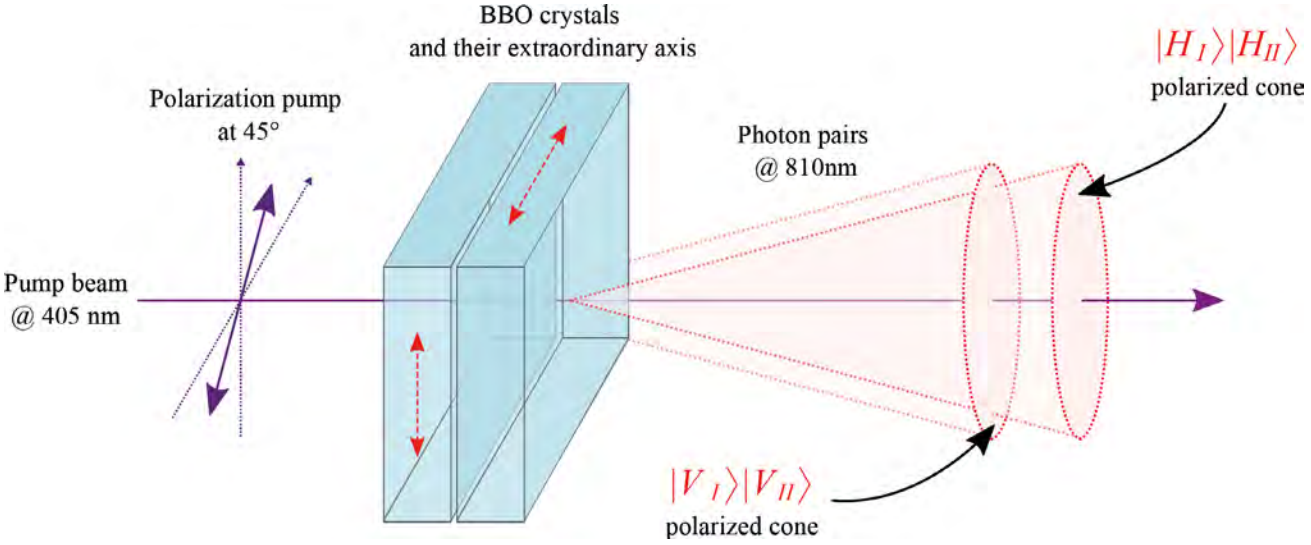


Figure 3. Two-crystal downconversion source: The crystals are 0.5 mm thick and in contact face-to-face, while the pump beam is approximately 1 mm in diameter.

An overview of the labwork setup

This experimental setup was proposed in the early 2000's [2,5]. What limited many experiments a few decades ago was the difficulty to create a bright source of photon pairs. A convenient way to proceed is to use a type I phase matching spontaneous parametric downconversion process in nonlinear crystals, see figures 2 and 3. The pump, a 60mW at 405nm blue InGaN laser diode, gives 810nm entangled photons. We will come back later to the detailed description of the Bell's state preparation. Downconverted photons are collected by two lenses (focal length: 75mm, diameter: 12.5mm) at about one meter from the crystals and focused on single photon counting avalanche photodiodes. Filters at 810nm, 10nm width, are placed just in front of each lens. Polarization is analysed by rotating the half wave plates in front of the polarization beam splitter cubes.

Black plastic tubes prevent from stray light and protect single photon counting modules. For each detected single photon, these modules give a 25ns TTL pulse which is sent to a coincidence detector to ensure that the coincidences are measured between photons of the same downconverted pair. In our experiment, for single detection rates of about 23000 on each side, we detect a coincidence rate of about 1600 (that is 1600 pairs of photons persecond).

Bell state preparation

The key of the setup is the preparation of a pure entangled state, one that will make sure that we can discriminate between hidden variable theories and quantum mechanics. We shall create photon pairs through a process that will indistinguishably generate either $|H_I\rangle|H_{II}\rangle$ or $|V_I\rangle|V_{II}\rangle$ in a superposition state (and not in a statistical mixture).

To produce polarization entangled pairs of photons, we use two identical thin crystals, rotated by 90° from each other about the pump beam direction (see figure 3). For a vertically polarized pump, the down-conversion process generates pairs of horizontally polarized photons in the first crystal; the second crystal has no more effect. For a horizontally polarized pump, the first crystal has no effect; the down-conversion process generates pairs of vertically polarized photons in the second crystal.

$$|V_{pump}\rangle \rightarrow e^{i\varphi H}|H_I\rangle|H_{II}\rangle$$
$$\text{and } |H_{pump}\rangle \rightarrow e^{i\varphi V}|V_I\rangle|V_{II}\rangle$$

For a rectilinearly polarised pump at 45°, the pump photons state is written as:

$$|\psi_{pump}\rangle = \frac{1}{\sqrt{2}}\left(|V_{pump}\rangle + |H_{pump}\rangle\right)$$

In this configuration, 45° polarized pump photons can down-convert in either crystal. **But it is absolutely impossible to know in which crystal the photon pairs were created!** By erasing this "which crystal information", we ensure that the photon pairs are in the superposition state:

$$|\psi_{2ph}\rangle = \frac{1}{\sqrt{2}}\left(|V_I\rangle|V_{II}\rangle + e^{i\varphi_0}|H_I\rangle|H_{II}\rangle\right)$$

Where φ_0 is a phase which depends on many different parameters (wavelengths of pump and down-converted photons, for example), and is a direct consequence of the birefringence of the crystals.

In practice, to get a pure Bell's state, we pre-compensate this phase by placing a Babinet compensator in front of the pair of crystals. The role of the Babinet compensator is to introduce a relative phase between $|H_{pump}\rangle$ and $|V_{pump}\rangle$:

$$|\psi^{Babinet}_{Pump}\rangle = \frac{1}{\sqrt{2}}\left(|V_{pump}\rangle - e^{-i\varphi_0}|H_{pump}\rangle\right),$$

The measurement of a Bell parameter is now routinely used with various quantum systems, in order to evaluate their performances in the context of quantum technologies.

leading to a pure Bell's state :

$$|\psi_{EPR}\rangle = \frac{1}{\sqrt{2}}\left(|V_I\rangle|V_{II}\rangle + |H_I\rangle|H_{II}\rangle\right),$$

For this state, the joint probability of detection in the $\langle V_I^{45°}|\langle V_{II}^{45°}|$ configuration reaches a maximum. The Babinet compensator is adjusted while monitoring the coincidence rate until it reaches an optimum for $\alpha = \beta = 45°$.

Results

The Bell parameter is measured by using a configuration of the four measurement basis that maximizes the deviation between local hidden variable theories and quantum mechanics. It is given by the angles $\alpha = 0°$, $\beta = 22.5°$, $\alpha' = 45°$, $\beta' = 45°$.

In our experiment, we obtain $S_{bell}(\alpha, \alpha', \beta, \beta') = 2.48$ with a standard deviation $\sigma = 3.10^{-3}$. The result shows that we do not reach an ideal entanglement quality ($S_{bell} = 2\sqrt{2}$), but it clearly and unambiguously disagrees with any hidden variable local theory.

Conclusion

Since the eighties, the EPR paradox is no longer a "Gedankenexperiment". Now, it has become a very exciting labwork for students. It also has recently taken another dimension: the measurement of a Bell parameter is now routinely used with various quantum systems, in order to evaluate their performances in the context of quantum technologies.

This labwork therefore now echoes with other ambitions aiming at building more advanced experimental training platforms for the second quantum revolution. Talking about indistinguishability, the Lense has been proposing for now more than 8 years a labwork dedicated to the Hong-Ou-Mandel effect, a two-particle interference experiment allowing to quantify the indistinguishability of photons generated by a similar downconversion process. Another setup under construction will be dedicated to the study of nitrogen vacancy centres in diamond, and their behaviour as single photon sources. ●

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