QUANTUM CORRELATIONS AND ENTANGLEMENT

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In 1935, Schrödinger introduced the word "entanglement" to describe a situation examined in the famous Einstein-Podolsky-Rosen paper published a few months before. The proper nature of quantum correlations that exist when a two-partite system is in an entangled state was a subject of controversy. In contrast to many other subjects, the debate about the nature of entanglement came quite recently to an end.

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After a period of gestation in the first quarter of the XXth century, Quantum Mechanics, as a comprehensive *ab initio* theory that could be applied to any physical situation, opened up a new era of physics, as it was able to describe in a quantitative and accurate way many systems: atoms, molecules, solids, electromagnetic fields ... Because of this amazing success, there was no doubt among the community of physicists concerning the validity of quantum theory and of its predictions. But this was not the case for the precise understanding of the concepts introduced, which have been, and are still, the object of debate [1]. Schrödinger, as a start, introduced the wavefunction $\psi(\mathbf{r})$ without knowing the exact nature of it. Born postulated that its square gives the probability of presence at point $\mathbf{r}$ and stressed the fundamental stochastic character of the measurement in quantum mechanics. He wrote it in a short footnote at the bottom of his paper [2], and for these few words he was rewarded with the Nobel prize! This in turn raised a wealth of questions: does the wavefunction, and more generally the state vector $|\psi\rangle$, describe a single particle or an ensemble of particles? Is the intrinsic randomness of the measurements a fundamental feature of the quantum world, or the reflection of our present ignorance? These questions, and many others, were the object of intense discussions, in particular between Einstein and Bohr, at the occasion of the Solvay meetings, and contributed to clarify, if not solve, the issues at stake. Following the 1935 "EPR" paper of Einstein, Podolsky and Rosen [3], and the reactions to this paper by Schrödinger [4] and Bohr, •••

the discussion focussed on the description of two-particle states and on the characterization of correlations between the measurements performed on these particles, their analogies and differences with the classical ones.

Let us take as an example the polarization states of two photons, labeled 1 and 2. We note $|V_1\rangle|V_2\rangle$ the quantum state of two photons of vertical polarization, and $|H_1\rangle|H_2\rangle$ the state of two photons of horizontal polarization. A basic feature of Quantum Mechanics is the superposition principle, which states that any linear combination of quantum states is another bona fide quantum state. It has been popularized by Schrödinger with his famous cat, superposition of a dead cat and an alive cat. We can therefore consider the state

$$|\psi_{12}\rangle=\frac{1}{\sqrt{2}}(|H_1\rangle|H_2\rangle+|V_1\rangle|V_2\rangle)$$

It is easy to show that this state cannot be written as a product of separate polarization states for each photon, so that is not possible to ascribe any polarization state to them separately. The two-photon state must be considered globally. If one measures the polarization of photon 1 using a polarizer of vertical orientation we have 50% probability of finding him with polarization V or H. If we find H for example, the measurement projects the quantum state of photon 1 on state $|H_1\rangle$ and therefore the global state $|\psi_{12}\rangle$ collapses on state $|H_1\rangle|H_2\rangle$. We are therefore sure that the polarization of photon 2 is also H, even when the two photons have been detected very far from each other. The same reasoning is true for a V measurement. There is therefore a perfect correlation between the measurements made on the two photons. For this reason the state $|\psi_{12}\rangle$ is named an entangled state, the english translation of the German word "Verschränklung" introduced by Schrödinger, who coined this property, "not as ONE, but rather as THE characteristic trait of quantum mechanics". This puzzling behaviour does not require any physical link between the two photons, just the application of basic quantum mechanics rules. The argument can be extended to measurements using polarizers of different orientations than vertical and horizontal that also exhibit correlations.

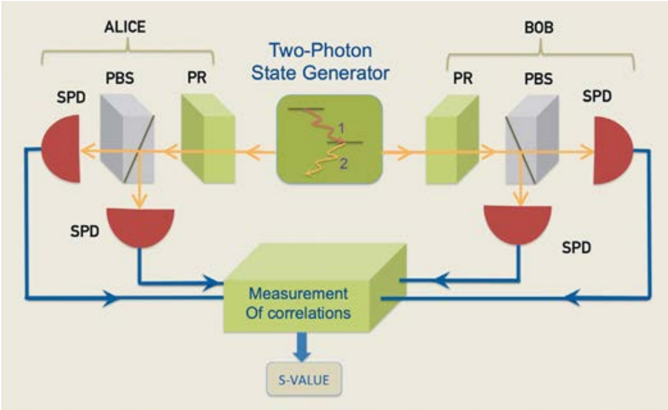

Figure 1: Sketch of an experimental set-up testing Bell inequality on a polarization-entangled two photon state. PR: polarization rotator; PBS: polarizing beamsplitter; SPD: single photon detector.

Of course, correlations do exist also in the classical world. They are even often the basis of scientific approach in many domains of science, for example in sociology, where correlations between apparently unconnected parameters constitute a privileged way to find causal chains. Let us consider the following classical situation: a jeweller, named J, has a stock of earring pairs, 50% in silver, 50% in gold. J randomly choses one pair and sends one earring of the pair to Alice (A) in Australia, and the other to Beatrice (B) in Brazil. When A receives her earring, she finds that it is for example a gold one. She then immediately knows, whatever the distance between them, that B will receive also a gold one. This is a classical case of perfect correlations. Though it seems that some kind of information has been transmitted instantaneously, there is no superluminal effect, because the information that A has on B's jewel is "private". The information is effective and measurable only when A sends a mail to B to communicate him the list of earrings she has received, so that Bob can effectively compare to its known list and measure the correlation.

The classical and quantum situations that we have just described seem at first sight quite similar. This is however not the case: in the classical example, each earring sent by J is made of a definite metal, a "solid" property that is carried all along by the earring. In the quantum example, there is no predetermined value of the spin orientations at the level of the entangled state generation. In addition, the randomness of measurements in the classical example arises from the random choice of earring pairs made by J, not from the probabilistic nature of quantum measurements.

A tempting resolution of the puzzling aspects of the quantum case is to mimic the classical situation by introducing for the two components of each photon pair a "tag" that identifies their common polarization and is carried all the way to Alice and Bob detectors. The value of this tag, named "hidden parameter", is not controlled, so that one has access only to averages over the values of this parameter. This simple picture leads to values of polarization correlations that are identical to the quantum prediction.

The introduction of a supplementary variable implies that the present state of quantum physics is not complete. The possible future mastering of this parameter would eliminate the random character of the quantum measurements. This interpretation of Quantum Mechanics was defended by Einstein (every physicist has in mind his famous statement: "The Old One does not play dice").

In 1964, John Bell made two astonishing discoveries [5]:

- He proved mathematically that the existence of hidden variables is not just a philosophical position. It indeed implies a constraint on measurement results. It showed more precisely that the introduction in the theory of local (i.e. attached to each photon) supplementary variables has indeed a physical consequence: it implies a maximal value of 2 for a well-defined combination, labeled S, of correlations between polarization measurements made by Alice and Bob with two different settings of the polarizer orientations. This is the famous "Bell inequality", which shifted the debate about hidden variables to the domain of experimental physics.
- He also exhibited specific experimental situations for which, according to the ordinary laws of quantum mechanics, one predicts a value of S bigger than 2 (Note that many entangled states do not violate Bell inequality).

Bell's discovery triggered a whole series of experiments [6,7]. In the oldest ones, performed in the 1970's, the entangled state was created by cascaded spontaneous emission on two successive atomic transitions, with two possible paths to the ground state. Most pairs of photons were lost because spontaneous emission is not directional, giving rise to a poor signal to noise ratio. One of the first experiments gave even an unexpected value of S smaller than 2. In experiments performed later in Berkeley and Houston, at the end of the 1970's, the use of laser excitation and improved detection schemes gave S values well above the noise floor. In the beginning of the 1980's the experiment by A. Aspect and coworkers yielded values of S unquestionably above 2, by more than 40 standard deviations. At the end of the 1990's spontaneous parametric down conversion in $\chi^{(2)}$ nonlinear crystal replaced cascades to generate the two-photon polarization entangled states. Phase matching conditions give rise to signal and idler photons emitted in small solid angles, resulting in a significant increase in the quantum efficiency of detection. Nowadays, Bell inequality is strongly violated, and in a short integration time, in photonic systems, but also using two spin 1/2 entangled particles [9].

Such experimentally proven violations of Bell inequality convinced an overwhelming majority of physicists to reject local hidden variables. The debate was actually closed in the 80's, after the Orsay experiments including a fast change of polarization settings during the photons time of flight. However, some theorists raised objections related to the unavoidable imperfections of the experimental protocols. These objections, named "loopholes", are sound from a purely logical point of view, and as such deserve to be examined, but they imply very improbable behaviours of the experimental set-up (a kind of "detector conspiracy") that are very unphysical. Objections concern the possibility of interaction information exchange between Alice and Bob polarization detectors, and a possible "unfair sampling" of the data that were detected, considering the limited collection efficiencies of the photon pairs. Starting from 1981 more and more sophisticated experimental set-ups strived to close this loopholes.

Finally in 2015, the results of 3 "loophole-free" experiments were published [8-11]. Let us briefly describe the one performed by M. Giustina and co-workers in A. Zeilinger's group in the basement of the Hofburg castle in Vienna [10]: the entangled state is generated by spontaneous parametric down conversion in a periodically poled nonlinear crystal and collected in two single mode fibers, at a rate of 3000 pairs per second. While the photons are in flight, fast random number generators choose the two polarization measurement settings. The distances between Alice, Bob, and the entangled state generator, of 30m, are large enough to prevent any kind of causal physical link between them. The detector quantum efficiency is 98%, thanks to the use of TES supraconducting Single Photon Detectors amplified by SQUID. In these optimized experimental conditions, Bell inequality is violated by 11.5 standard deviations on a sample of $3{,}5.10^9$ photon pairs.

After these experiments no serious physicist can now object that the hypothesis of local realistic hidden variables is ruled out by experiments and that an entangled state must be considered as a global, inseparable, entity whatever the distance between its two parties. In addition we must admit that the randomness of Quantum measurements cannot be related to our lack of knowledge about the system. The non-existence of random hidden parameters tells us that it will not be possible to predict for example when exactly an atom will decay by spontaneous emission: the quantum randomness is intrinsic.

Let us finally stress that Bell inequality violating entangled states are not only objects of basic theoretical interest. They are now privileged quantum resources used in applications, such as Quantum Key Distribution and Quantum Teleportation.

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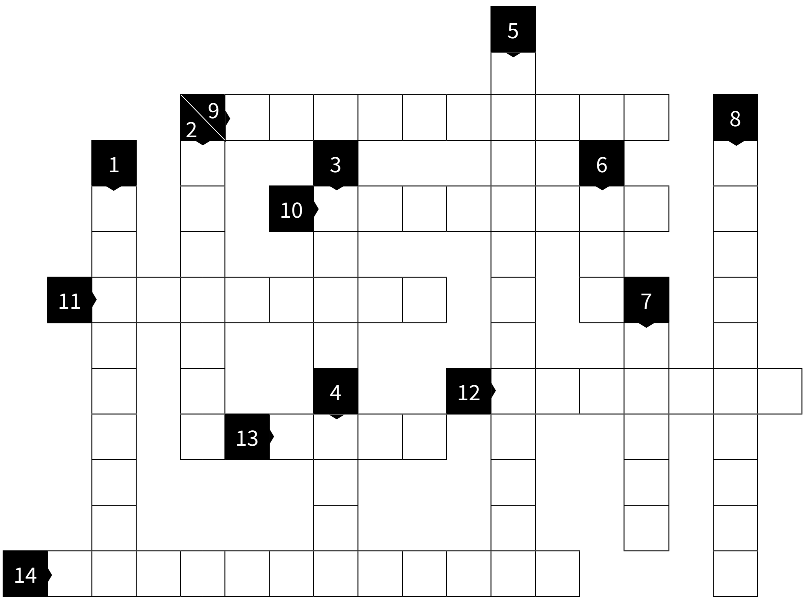

1 Property of a quantum operator
2 Big atoms
3 Up or down
4 Inequality
5 Obeys the Schödinger equation
6 Paradox
7 Bob's friend
8 Only with bosons
9 Physical quantity that can be measured
10 States with less uncertainty in one quadrature
11 First condensate
12 Doppler, Sisyphus or evaporative
13 Basic unit in quantum computing
14 Only in quantum mechanics