The Einstein-Podolski-Rosen paradox and the Notarrigo experiment

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Beatus ille qui procul negotiis […]
[…] *quid enim concurritur* […]
Q. Horatius Flaccus, *Epodi, Satire*

Abstract: My contribution celebrates the enthusiastic ferment of ideas around the Einstein-Podolski-Rosen paradox, stimulated by Notarrigo during the period 1972-1980 in our Physics Department. The wide discussions on the fundamentals of Quantum Mechanics, and in particular of some of its principles, determined a strong effort for the realization of an experiment aimed to a verification of the crucial points raised by the paradox.
I will briefly summarize the theoretical debate and I will try to describe the experimental set-up conceived by the Notarrigo group, based on the detection of the polarization correlation of the two annihilation photons produced by e^+, e^- couples in singlet state, after having been scattered by two plastic scintillators and revealed by two detectors. Our preliminary results, situated along the Bell limit for the possible existence of "hidden variables", afterword confirmed more and more the validity of Quantum Mechanics.

Keywords: EPR paradox, EPR test by annihilation photon correlation.

1. Introduction

At the beginning of 1970, back from MIT (Massachusetts Institute of Technology, Cambridge, Boston, USA), where I spent a year as a visiting scientist, Totò Notarrigo asked me to join his experimental group for investigating the foundations of Quantum Mechanics. He needed my collaboration because of my previous experience in the field of positron annihilation. In fact, my thesis work in 1965, and the experiments performed afterword in Frascati and in Frankfurt were related to annihilation photons angular correlation in metals and semiconductors observed by this technique. With great enthusiasm I accepted and participated in a seminar where Notarrigo presented the famous article of Einstein, Podolsky, Rosen (Einstein *et al.* 1935).

The seminar raised a great interest. A wide debate on quantum foundations involved many colleagues actively participating with seminars, notes, ideas, discussions. In particular, I remind the following topics:

1. The principle of superposition of states in quantum mechanics and the paradox of the Schröndiger's cat (Schrödinger 1935; Selleri 1988; Omnès 1992; Belinfante 1973);
2. The uncertainty principle and the Heisenberg relations (Schrödinger 1935; Selleri 1988; Omnès 1992; Belinfante 1973);
3. Realism and locality (Schrödinger 1935; Selleri 1988; Omnès 1992; Belinfante 1973);
4. Incompleteness of quantum theory (Schrödinger 1935; Selleri 1988; Omnès 1992; Belinfante 1973);
5. Quantum entanglement (Schrödinger 1935; Selleri 1988; Omnès 1992; Belinfante 1973);
6. Hidden variables and the von Neumann arguments (Schrödinger 1935; Selleri 1988; Omnès 1992; Belinfante 1973);
7. Bell theorem (Schrödinger 1935; Selleri 1988; Omnès 1992; Belinfante 1973);
8. Theory of the measurements according to Bohm, and the pilot wave of de Broglie. The Copenhagen interpretation (Schrödinger 1935; Selleri 1988; Omnès 1992; Belinfante 1973).

The discussions determined the agglomeration of two experimental groups; to the first participated Salvatore Notarrigo, Agata R. Pennisi, Diego Gutkowski and myself, with the aim of testing the EPR paradox by using the scattering of annihilation photons (Faraci *et al.* 1974). To the other, directed by Vittorio Rapisarda, joined Mariella Oliveri, Lorenzo Pappalardo, Filippo Falciglia and external collaborators, with the same objective but using the photons of calcium cascade (Baldo *et al.* 1981; Falciglia *et al.* 1982).

2. The Einstein paradox

The elements of physical reality are tightly dependent on the results of experiments. A satisfactory theory, according to Einstein (Einstein *et al.*1935), should be "complete" in the sense that "every element of the physical reality must have a counterpart in the physical theory". The question arises: "is quantum mechanics a complete theory?"

In quantum mechanics, if the operators corresponding to two physical quantities, e.g., the position and the momentum of a particle, do not commute, the exact determination of one of them implies that the other is completely undefined. Therefore, quantum mechanics is not a complete theory in the sense that coupled physical quantities, as described by the quantum wavefunction, cannot have simultaneous reality. These physical quantities are called "entangled" and measurements on an entangled system are the object of the Einstein *gedanken* experiment. I describe here a typical *gedanken* experiment performed on a system breaking into two correlated entangled photons, traveling in opposite directions (Aspect 1999; Aspect *et al.* 1982). This is the case of a laser excitation of an atomic radiative cascade.

Let us suppose that the photons are orthogonally polarized. If, traveling in opposite directions, their polarizations are detected when they are so far apart that no signal can establish a mutual communication between them, the detection along an arbitrary direction of a polarization implies the exact knowledge of the other. This is not acceptable, because the measurement of a polarization along a direction causes quantum reduction, its result is given by a probability distribution related to the detection direction, and the two photons cannot "communicate" with each other without violating the relativity principles. Therefore, how can the second photon give the correct answer for its polarization measurement whatever is the result of the first one?

These problems were strongly debated from a pure and theoretical point of view between the followers of Einstein and those of the Copenhagen statistical interpretation till the publication of a famous paper by John Bell (Bell 1964), dramatically modyfing the nature of the debate. Bell demonstrated in fact that an algebraic inequality can be written, contradicted by quantum mechanical predictions in an experimental test involving polarizer orientations of an entangled system.

3. Bell's inequality

The argument given by J.S. Bell in 1964 is the following (Bell 1964): if we consider a system in the singlet state decomposing in a pair of spin one-half, moving in opposite directions, we can measure a component of the spin along an arbitrary direction. When such measurement is performed on the spin σ_1 along a direction $\vec{\boldsymbol{a}}$ giving a value +1, the similar measurement of σ_2 along $\vec{\boldsymbol{a}}$ must yield –1 according to quantum mechanics. If the two measurements are simultaneously performed at distant places, no signal can permit any communication between the two detecting apparata, without violating the relativity principle. Being the two spins correlated, we can predict in advance the result of measuring σ_2, if we have determined the same component of σ_1. This implies a predetermination of such result, not contemplated by quantum mechanics.

Bell argued that a more complete specification of quantum states by means of "hidden variables λ" should be hypothesized. Bell demonstrates that, if now the result A of measuring $\vec{\sigma}_1 \times \vec{\boldsymbol{a}}$ is determined by $\vec{\boldsymbol{a}}$ and λ, and similarly B the measurement of $\vec{\sigma}_2 \times \vec{\boldsymbol{b}}$ is determined by $\vec{\boldsymbol{b}}$ and λ, the expectation value of the product of the two components:

$$< \vec{\sigma}_1 \times \vec{\boldsymbol{a}} \quad \vec{\sigma}_2 \times \vec{\boldsymbol{b}} > \text{ is given by}$$

$$\mathrm{P}(\vec{\boldsymbol{a}}, \vec{\boldsymbol{b}}) = \int \rho(\lambda)\ \mathrm{A}(\vec{\boldsymbol{a}}, \lambda)\ \mathrm{B}(\vec{\boldsymbol{b}}, \lambda)\, d\lambda$$

where $\rho(\lambda)$ is the normalized probability distribution of the hidden variables λ.

This result, however, is not entirely compatible with the quantum mechanical value $-\vec{\boldsymbol{a}} \times \vec{\boldsymbol{b}}$. In fact Bell demonstrates a famous inequality:

$$|\mathrm{P}(\vec{\boldsymbol{a}}, \vec{\boldsymbol{b}}) - \mathrm{P}(\vec{\boldsymbol{a}}, \vec{\boldsymbol{c}})| \leq \mathrm{P}(\vec{\boldsymbol{b}}, \vec{\boldsymbol{c}}) + 1$$

which is violated by quantum mechanics (Aspect *et al.* 1982; Bell 1964).

Several experiments were conceived for testing the QM predictions, comparing Bell's expressions derived from a possible introduction of hidden variables. In particular, I recall the Holt and Pipkin experiment (Clauser, Horne 1974), and the Clauser, Horne, Shimony and Holt proposal (Clauser *et al.*1969) etc.

Most of them aimed to determine the two photon polarization correlation in entangled systems, under "ideal conditions" using polarization analyzers such as Nicol prisms and similar. The question was whether for such experiments involving two-photon polarization correlation quantum theory can contradict any hidden variables theory.

The photon polarization correlation can be measured through coincidence rates at a given angle of polarizer #1, with respect to the angle of polarizer #2.

Denoting $P_{x,y}(\vec{a},\vec{b})$ the probability of obtaining a result x = +1, along $\vec{a}$ for the photon #1 (when a measurement along $\vec{a}$ yields the value +1, i.e., polarization parallel to $\vec{a}$), or x = –1 (polarization orthogonal to $\vec{a}$), and similarly for y = ±1 for photon #2 along $\vec{b}$, the quantity to be calculated is (Aspect *et al.* 1982):

$$\Delta(\vec{a},\vec{b}) = P_{++}(\vec{a},\vec{b}) + P_{--}(\vec{a},\vec{b}) - P_{+-}(\vec{a},\vec{b}) - P_{-+}(\vec{a},\vec{b}).$$

A combination for different orientation a, a′, b, b′, can be built such as:

$$S = \Delta(\vec{a},\vec{b}) - \Delta\left(\vec{a},\ \vec{b}'\right) + \Delta\left(\vec{a}',\vec{b}\right) + \Delta(\vec{a}',\vec{b}').$$

For the previous expression Bell's inequalities give: $-2 \leq S \leq +2$, whereas QM for an appropriate set of angles (22.5°, 67.5°) can reach a value $S=\pm 2\sqrt{2}$ (Fig. 1).

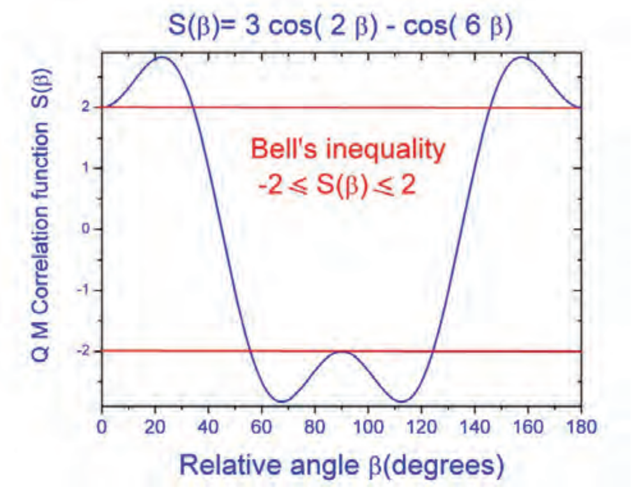

Fig. 1. Correlation function S(β) as a function of the relative angle. As clearly visible, quantum mechanical predictions for several angular values are larger than Bell's data

The experimental results as soon as the accuracy of the measurements was good enough completely agreed with quantum mechanics.

4. The annihilation photons

A couple electron-positron (e^-, e^+) in the singlet state annihilate into two photons of 0.511 MeV, moving in opposite directions. The polarizations of the photons are correlated in orthogonal directions, and therefore could be used for testing the Bell inequality, as discussed above. However, the detection of the polarization for such high energy photons cannot be performed with an ideal polarizer, as Nicol prism, but requires an indirect analysis using the Klein-Nishina formula of the scattering cross section:

$$W(\theta_1, \theta_2, \varphi) \propto K_1^2 K_2^2 \int \{\gamma_1\gamma_2 \text{-} \gamma_1 sin^2\theta_2 \text{-} \gamma_2 sin^2\theta_1 + 2sin^2\theta_1 sin^2\theta_2[(2k-1)sin^2\varphi + (1-k)]\} \quad (1)$$

where K_1, and K_2, are the outgoing photon (#1, #2) wavenumbers, K_0 is the ingoing photon wavenumber, $\gamma_{1,2} = K_{1,2}/K_0$; θ_1, θ are the scattering angles, φ is the azimuthal angle (see Fig. 2) and k a correlation parameter related to the probability of observing the photon pair with orthogonal linear polarization (Faraci *et al.* 1974).

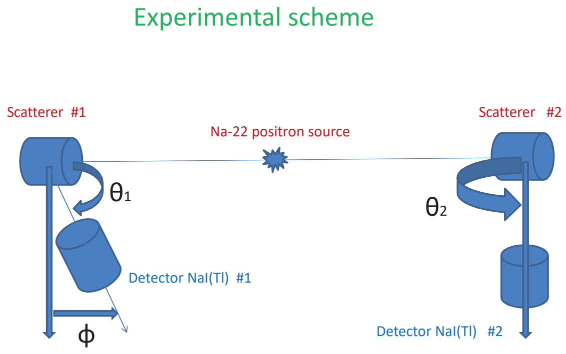

Fig. 2. Experimental set up showing the positron source, the two scatterers and the two detectors, producing the 4 signals put in coincidence

5. Experimental set-up

An experimental set-up was planned in 1972 by the Notarrigo's group (Fig. 3) according to the scheme shown in Fig. 2.

In a plexiglass annihilator material a positron radioactive source of ^{22}Na was put, in order to obtain two-photon emission traveling in opposite directions defined by means of lead radiation collimators. Two plastic scintillators (NE 202) act as scatterers of each 0.511 MeV photon, which after the scattering can be detected at a defined angle θ by a NaI(Tl) detector. Fixing the scattering angles θ_1, θ_2 and the azimuthal angle φ, the 4 signals from the two scatterers and the two detectors are put in quadruple coincidence with a 30 ns resolving time, giving the coincidence counting rate $N(\theta_1, \theta_2, \varphi)$. This rate can be related to the correlation function (1). The ratio $N(\theta, \theta, \varphi)/N(\theta, \theta, 0°)$ expresses the anisotropy as a function of the azimuthal angle, for fixed scattering angle.

Fig. 3. G. Faraci (left) with Salvatore Notarrigo under the volcano Fujiama, during the Yamanaka conference in April, 1979

The experiment required a great effort for the determination of several corrections which are here mentioned only schematically (Faraci *et al.* 1979; Faraci *et al.* 1980; Faraci 1982; Faraci, Pennisi 1985; Faraci, Pennisi 1986):

a. the geometrical distribution of the radioactive source, the emission cones of the photons and the shielding collimators;
b. the scattering effective points inside the scatterers. This problem was solved by a specific subroutine concerning “random numbers”;
c. the cross section for Compton or photoelectric events in each detector,
d. the correction for borderline events;
e. the events sequence, requiring a Fibonacci-like series;
f. the correction for dead-time width of each electronic signal;
g. the dead-time distorted Poisson process;
h. the quadruple coincidence and the acquisition system for optimize the counting rate with respect to the spurious counts.

All the problems encountered were studied, checked and inserted in a very complicated Monte Carlo program simulating the experimental situation, in order to correct the acquired data.

Our preliminary results were published in 1974 (Faraci *et al*. 1974), giving an anisotropy ratio just on the Bell's limit.

The final results were presented at the Yamanaka meeting held in Japan in 1979. As the corrections introduced by the Monte Carlo program were more and more accurate, the experimental results were completely confirming the quantum previsions.

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