Quantum correlations with spacelike beamsplitters in motion

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One of the most peculiar features of quantum mechanics is the non-local property of some quantum states (e.g. the singlet state). The experimental violation of Bell's inequality demonstrates that the outcome of the measurement on one particle depends of the measurement settings on the other particle, even when both measurements are spacelike separated. Although this property is non-local according to special relativity, it cannot be used to transmit supraluminal signaling.

Classically, correlations between 2 events can be explained by 2 mechanisms. Either there is a common cause between both events or there is a communication between them. Because of the experimental violation of Bell's inequality when the settings are set outside the light cone of each other, quantum correlations cannot be explained by common causes. However no experiment has ruled out a possible supraluminal communication between the events.

If there were a real supraluminal physical process, this would imply a logical (and temporal) ordering of the events, one being the cause of the other. However this ordering for space-like events is not Lorentz invariant and would depend of the reference frame. Hence a preferred reference frame has to be introduced, recalling that this is only the frame of the quantum process and does not implies supraluminal signaling. The preferred frame could be a unique one, or a frame attached to the measurement device. To test this last hypothesis, we have set the measuring (or analyzing) devices such that each one is the first to see its particle in his own reference frame (*before-before* case). In that case, the correlations should disappear, as there is no more defined temporal ordering. The last remaining question is the nature of the analyzing device. This is related to the measurement problem. Our experiment follows an experiment, which has be done with moving detectors and assumed that the collapse is a real process occurring at the detection. As this first experiment didn't show any disappearance of the correlations, we have considered the beam-splitters as the relevant reference frame. This is inspired by the de Broglie and Bohm pilot-wave picture in which the particle and the wave always co-exist, the wave guiding the particle and the particle triggering the detectors. The theory we tested, Multisimultaneity is a relativistic generalization of this assumption.

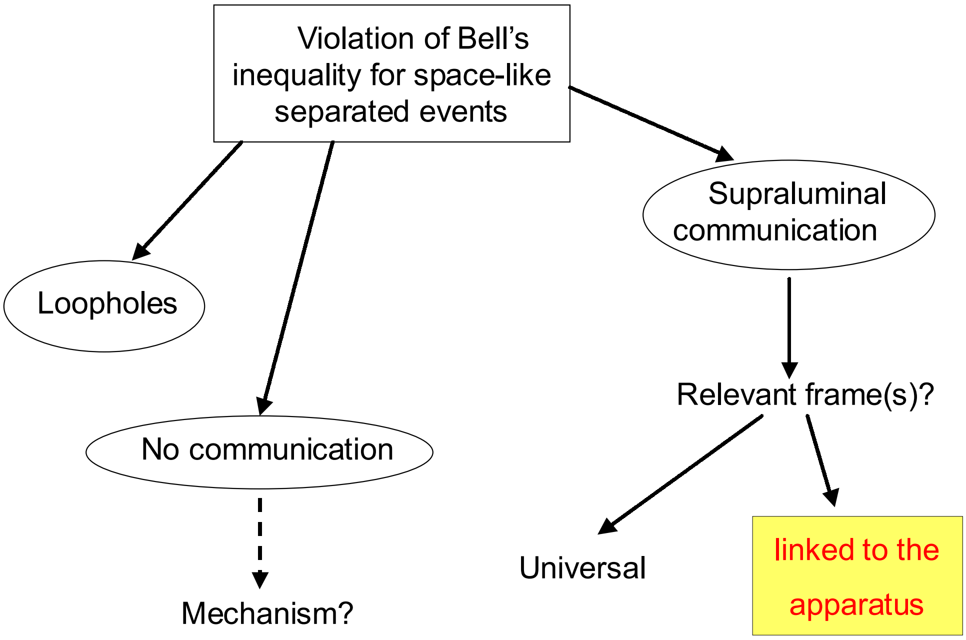
This experimental test of quantum correlations has been done with energy-time entangled pairs of photons. We used the Franson 2-photon interferometric setup with AOMs (acousto-optic modulators) as moving beamsplitters. Indeed the acoustic traveling wave inside the material creates a change in the refractive index equivalent to a traveling diffraction grating, and the induced frequency shift is equal to the Doppler shift produced by a moving mirror.

By carefully setting the time of arrival of the photons and scanning it, we can be certain to reach the *before-before* situation. In this case the experiment didn't show any disappearance of the correlation. This stresses the oddness of quantum correlations. Not only the correlations are independent of the distance, but also it seems impossible to cast them in any real time ordering. One can't maintain any causal explanation in which an earlier event influences a later one by arbitrarily fast communication. In this sense, quantum correlations are a basic (i.e. primary) concept, not a secondary concept reducible to that of causality between events.

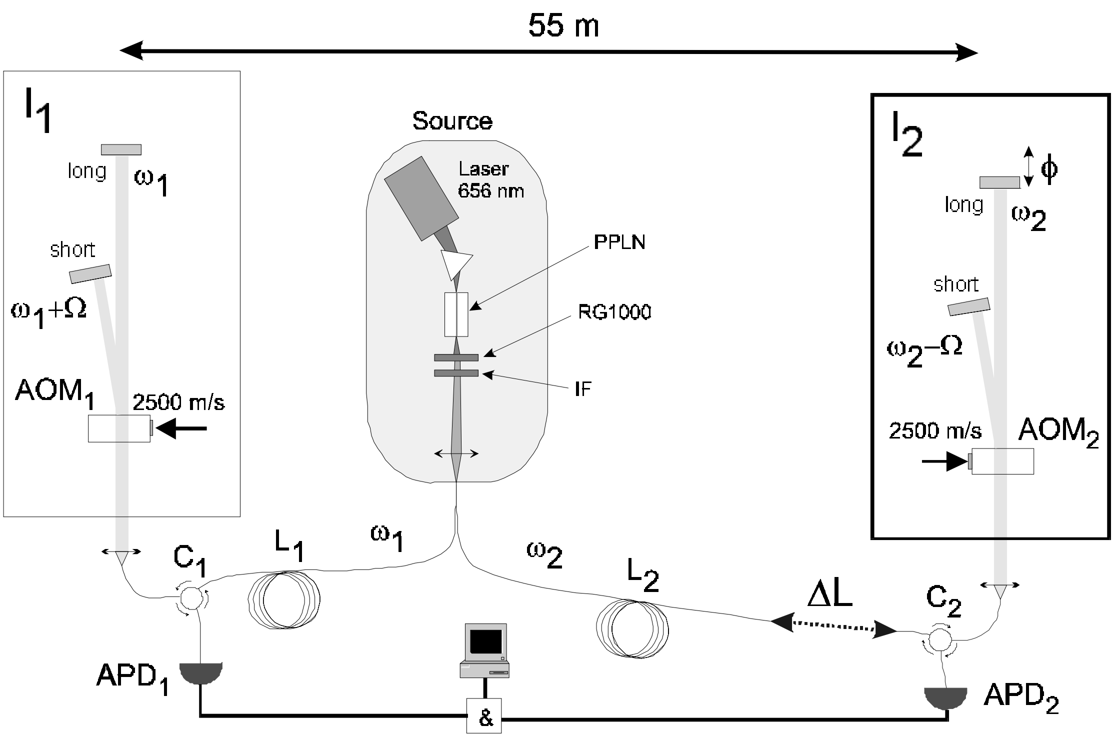
References:

- Quantum correlations versus Multisimultaneity: an experimental test, A. Stefanov, N. Gisin, A. Suarez, H. Zbinden, quant-ph/0110117, submitted to Physical Review Letters (available at: http://xxx.lanl.gov/abs/quant-ph/0110117) and references inside.

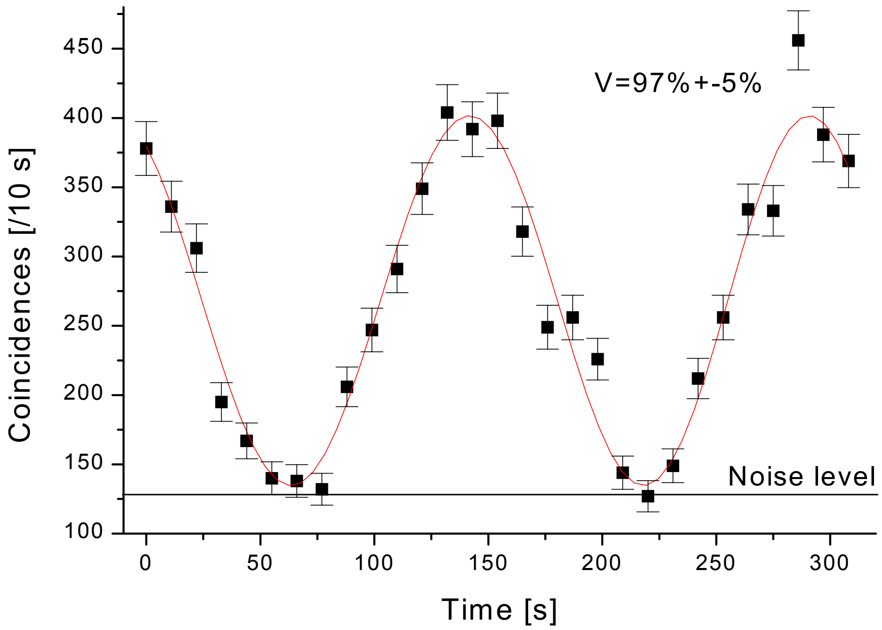
- "Spooky Twins Survive Einsteinian Torture", News of the Week, Science, 9 Nov. 2001, p. 1265 (www.sciencemag.org)



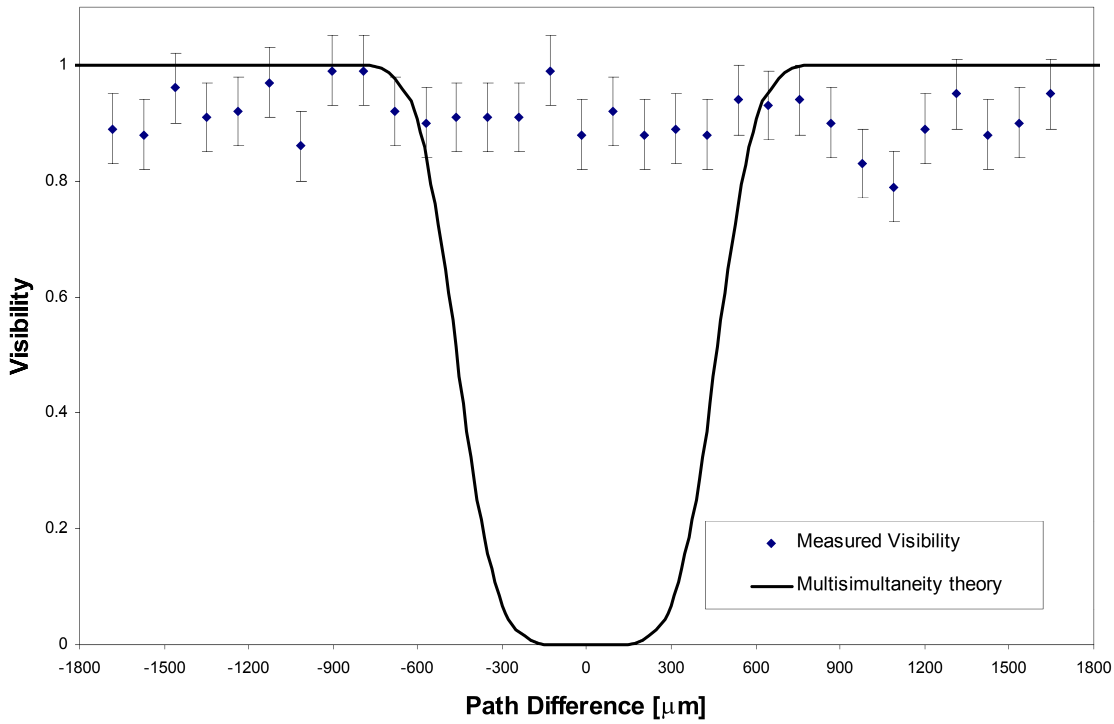
Schematic representation of the different explanations for the experimental fact of Bell's inequality violation. We have tested the hypothesis in the yellow frame.



Schematic of the experiment. Each photon of one pair created by a PPLN waveguide is coupled into an optical fiber (L_1 and L_2). An RG1000 filter blocks the pump laser and an 11 nm interference filter (IF) narrows the photon bandwidth. L_2 can be changed of ΔL by pulling on a fiber. Each photon is sent in an interferometer (I_1 and I_2), which uses an acousto-optic modulator (AOM) as beamsplitter. The AOMs are 55 m apart and oriented such that the acoustic waves propagate in opposite directions. Optical circulators C_1 and C_2 guide the photons coming out from the interferometers into avalanche photodiodes detectors (APD). The detection signals are sent to a coincidence circuit. As the frequency shifts are compensated, the total energy ($\omega_1+\omega_2$) when both photons take the short arms or the long ones is constant. 2-photons interference fringes are observed by scanning the phase ϕ with a moving mirror.



2-photon interference fringes with high visibility (97%) violating Bell's inequality by 5 standard deviations.



Visibility of the 2-photon interference vs. the difference of the photons times of arrival on the analyzers (express in optical path difference). According to Multisimultaneity theory the visibility should vanish on a range of about 700 µm. No disappearance of the correlations has been observed, thus confirming the frame-independence of Quantum Mechanics.