Quantum Correlations with Spacelike Separated Beam Splitters in Motion: Experimental Test of Multisimultaneity

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Multisimultaneity is a causal model of relativistic quantum physics which assigns a real time ordering to any set of events, much in the spirit of the pilot-wave picture. Contrary to standard quantum mechanics, it predicts a disappearance of the correlations in a Bell-type experiment when both analyzers are in relative motion such that each one, in its own inertial reference frame, is first to select the output of the photons. We tested this prediction using acousto-optic modulators as moving beam splitters and interferometers separated by 55 m. We did not observe any disappearance of the correlations, in agreement with quantum mechanics.

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Many experiments have demonstrated quantum correlations between spatially separated measurements, under several conditions [1], in perfect concordance with quantum mechanical predictions. The most striking feature of quantum correlations being the violation of Bell's inequalities [2].

In this Letter we confront quantum correlations with a natural alternative model, called multisimultaneity [3]. First, we summarize multisimultaneity, stressing its close relation to the famous pilot-wave model of de Broglie and Bohm [4]. Next, we oppose the predictions of quantum mechanics and of multisimultaneity in the situation where two entangled particles are analyzed by two beam splitters moving apart in such a way that each beam splitter in its own inertial reference frame analyzes his particle before the other. We argue that multisimultaneity is the natural application of the pilot-wave intuition to this configuration. Finally, we present an experimental test based on two-photon interferences.

Within Newtonian physics, where time is absolute, it is possible to describe quantum correlations at a distance in a causal time-ordered way [5]. One class of examples assumes that the collapse of the state vector is a real physical phenomenon [6–8]: the first measurement produces a collapse, and the second measurement happens on a system in the collapsed state.

Another explicit example, closer in spirit to the subject of this Letter, is provided by the pilot-wave model of de Broglie and Bohm. There the particle and the wave always coexist, the wave guiding the particle and the particle triggering the detectors. The two slit experiment is then not more difficult to understand than the evolution of a cork floating in a river: if an island separates the river in two over a certain length, then the cork passes on one (and only one) side of the island, but its subsequent evolution is also affected by the water that passes around the other side. When this model is applied to two entangled particles, the model is less intuitive (the "wave flows" in configuration space), but it still provides a well defined, "mechanistic" description, of how quantum correlations build up: the measurement on one side modifies the "wave" which in turn guides the distant particle (the model is local in configuration space, but nonlocal in real space). This model reproduces all quantum predictions. Further, if one assumes that a privileged reference frame (e.g., defined by the cosmic microwave background radiation) determines the time ordering, then this model is self-consistent. However, when time is relative, as in special relativity, it is ambiguous. Indeed, it is then no longer defined which measurement modifies the wave first and which particle is then guided.

Multisimultaneity is an attempt to set the pilot-wave intuition in a relativistic context. For this, one of the authors of this Letter, Suarez, together with Scarani, proposed a model in which a causal temporal order is defined for each measurement [3]. The basic idea is that the relevant reference frame for each measurement is the inertial frame of the massive apparatus. More specifically, multisimultaneity assumes that the relevant frame is determined by the analyzer's inertial frame (e.g., a polarizer or a beam splitter in our case). Paraphrasing Bohr, one could say that the relevant frame, hence the relevant time ordering, depends on the very condition of the experiment [9]. In multisimultaneity, as in the pilot-wave model, each particle emerging from a beam splitter follows one (and only one) outgoing mode, hence particles are always localized, although the guiding wave (i.e., the usual quantum state ψ) follows all paths, in accordance with the usual Schrödinger equation. When all beam splitters are at relative rest, this model reduces to the pilot-wave model and has thus precisely the same predictions as quantum mechanics. However, when two beam splitters move apart, then there are several (i.e., two) relevant reference frames, each defining a time ordering, hence the name of multisimultaneity. In such a configuration it is possible to arrange the experiment in such a way that each of the two beam splitters in its own reference frame analyzes a particle from an entangled pair before the other. Each particle has then to "decide" where to go before its twin particle makes its choice (even before the twin is forced to make a choice). Multisimultaneity predicts that in such a *before-before* configuration, the correlations disappear, contrary to the quantum prediction.

Let us emphasize that the model of multisimultaneity, although conceptually quite foreign both to quantum mechanics and to relativity, is not in contradiction with any existing experimental data. Furthermore, it has the nice feature that it can be tested using existing technology. Since it would have been very difficult to put conventional beam splitters in motion, we used traveling acoustic waves as beam splitters to realize a *before-before* configuration. It has been shown that the state of motion of the moving acoustical wave defines the rest frame of the beam splitters [10]. We stress that a before-before experiment using detectors in motion has already been performed confirming quantum mechanics, i.e., the correlations did not disappear [11,12].

Energy-time entanglement can be demonstrated by two-photon interference experiments [13]. In this experiment (Fig. 1) we use the Franson configuration [14]. Each photon from an energy-time entangled photon pair source is sent to an analyzer. Each one consists of an unbalanced interferometer, the difference between the long and short

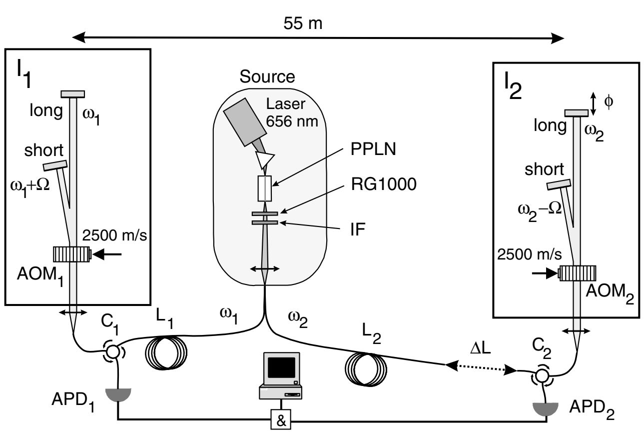

FIG. 1. Schematic of the experiment. Each photon of one pair created by the PPLN waveguide is coupled into an optical fiber (L_1 and L_2). An RG1000 filter blocks the pump laser and an 11 nm interference filter (IF) narrows the photon bandwidth. L_2 can be changed of ΔL by pulling on a fiber. Each photon is sent in an interferometer (I_1 and I_2), which uses an acousto-optic modulator (AOM) as beam splitter. 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 both the short arms or both the long ones is equal. Two-photon interference fringes are observed by scanning the phase ϕ with a moving mirror.

arms being much longer than the coherence length of a single photon. The coincidence events when both photons take the short arms or both the long ones are indistinguishable because the emission time is undetermined, due to the long coherence time of the pump laser. If we select only those events, the coincidence rate between the two outputs is proportional to

$$1 + V\cos(\phi_1 + \phi_2),$$

where V is the visibility and ϕ_1 and ϕ_2 are the phase differences between the long and the short arms in interferometers 1 and 2, respectively. Experimentally the visibility is always lower than 1 due, e.g., to detector noise and to partial distinguishability of the interfering paths. Nevertheless, it can be larger than 0.71, the maximal visibility compatible with any local theory [2].

We use a recently developed periodically poled lithium niobate (PPLN) waveguide source of energy-time entangled photons [15]. It features very high efficiency, so we can register interferences in shorter measuring times. Violation of Bell inequality has already been demonstrated with this source [16].

We built two unbalanced bulk Michelson interferometers using AOMs (acousto-optic modulators, Brimrose AMF-100-1.3-2mm) as beam splitters. An AOM can be seen as a realization of a moving beam splitter: the traveling acoustic wave inside the material changes the refractive index, thus creating a traveling diffraction grating. The reflection coefficient is maximal at the Bragg angle θ_B:

$$2\lambda_s \sin\theta_B = \lambda/n, \tag{1}$$

where λ_s is the sound wavelength, λ is the light wavelength in vacuum, and n the refractive index of the material. The reflection coefficient is given by $R = \sin^2(\sqrt{\alpha I})$ [17], where I is the acoustic power and α depends on the AOM size and material, and on the light wavelength. Hence, the acoustic power was set, such that the beam splitting ratio is 50/50. The AOM ends by a skew cut termination; thus the wave is damped rather than reflected. Hence it is effectively traveling and not stationary. A point which gives us confidence in using AOM [10] is that the reflection on a moving mirror produces a frequency change of the light, due to the Doppler effect, given by

$$\Delta\nu = \frac{2nv\sin\theta}{c}\nu, \tag{2}$$

where v is the mirror velocity and θ the angle between the incident light and the plane of reflection. Within an AOM the reflected light is also frequency shifted and the frequency shift is equal to the acoustic wave frequency (100 MHz in our case):

$$\Delta\nu = \nu_s. \tag{3}$$

Using $\lambda_s\nu_s = v_s$ for the sound wave and Eqs. (1) and (3) we found that the frequency shift induced by the AOM is the same as the one induced by a mechanical grating traveling at speed v_s.

The frequency shift induced by the AOMs on the reflected beam (200 MHz because it passes twice through the modulator) forces us to use an AOM in each interferometer; otherwise, the total energy of both photons would not be the same for the short-short and the long-long paths, leading to distinguishability between the two paths. Therefore both interferometers were made such that the shifts compensate, and the total energy remains the same. Moreover, both frequencies have to be exactly identical to avoid beatings. This requires that the frequency of both AOM rf drivers is synchronized [18].

Because of the small deviation angle (about 5°) of the interferometer arms, we collect only the light coming out from the input port by using a fiber optical circulator (see Fig. 1). As the deviation angle depends on the light wavelength, an AOM acts as a bandpass filter for the reflected beam with a bandwidth of about 30 nm. Therefore we have to ensure that the bandwidth of the photons is smaller by placing a spectral filter after the source. The transmission through each interferometer is about 0.25.

When the phase ϕ is changed by slightly moving back and forth one of the mirrors with a piezoelectric actuator, we observe two-photon interference fringes with a visibility up to 97% $\pm$ 5% after substraction of the accidental coincidences (Fig. 2). We observed that the visibility is very sensitive to a small difference in the electric spectra of the rf signals driving the two AOMs [18].

In order to test multisimultaneity, both interferometers have to be far away, and both photons have to reach the moving beam splitters at the same time. The criterion given by special relativity for the change in time ordering of two events in two reference frames counterpropagating at speed v is

$$|\Delta t| < \frac{v}{c^2}\, d\,, \qquad (4)$$

where Δt and d are, respectively, the time difference and distance between the two events in the laboratory frame [3]. This criterion is much more stringent than the space-like separation condition $|\Delta t| < \frac{d}{c}$. Because of the high speed of the acoustic wave (2500 m/s, specified by the manufacturer and computed from the mechanical properties of amorphous material transmitting IR [19]), a distance of 55 m between the interferometers is sufficient, allowing us to realize the experiment inside our building. The permitted discrepancy on the time of arrival of the photons at the AOMs is then, according to (4), ± 1.53 ps, corresponding to a distance of ± 0.46 mm in air. The fiber path length can be measured with a precision of 0.1 mm using a low coherence interferometry method. The error on the interferometers' path lengths is measured manually with a precision smaller than 0.5 mm. To be sure that we have set the lengths as required we scan the path length difference by pulling on a 1 m long fiber. The scan steps are of 0.12 mm. Simultaneously we keep scanning the phase to observe interferences.

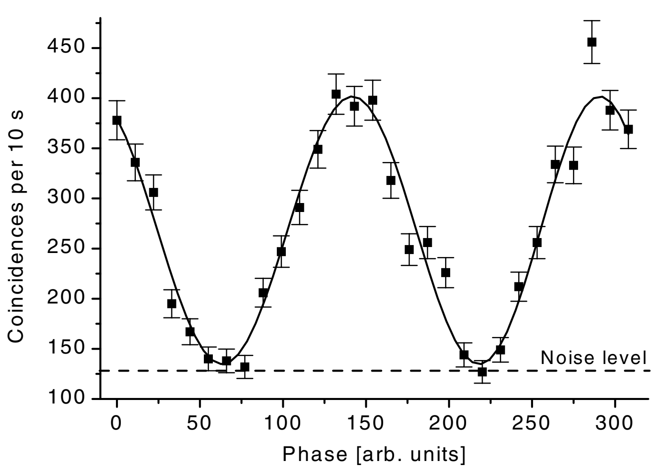

FIG. 2. Two-photons interference fringes. According to a sinusoidal fit, the visibility is 97% $\pm$ 5% after substraction of the accidental coincidences.

It is not sufficient to precisely equalize the path lengths, we also have to ensure that the coherence length of the photons is smaller than the permitted discrepancy. This is the case because, with the interference filter placed after the photon pair source, the photons coherence length is about 0.14 mm. Another effect to take into account is the chromatic dispersion in the fibers. This will spread the photon wave packet. However, thanks to the energy correlation, the dispersion can almost be canceled. The requirement for the two-photon dispersion cancellation [20] is that the center frequency of the two photon is equal to the zero dispersion frequency of the fibers. We measured this value on a 2 km fiber with a commercial apparatus (EG&G) which uses the phase shift method. We found a value of 1313.2 nm for λ_0. Then we used 100 m of the same fiber, assuming that the dispersion is equally distributed. We set the laser wavelength at half this value. The pulse spreading over 100 m, if we conservatively assume a 1 nm difference between the laser wavelength and λ_0, is 0.2 ps [11] corresponding to a length of 0.06 mm in air, which is much smaller than the permitted discrepancy.

According to the multisimultaneity model, the correlations should disappear on a range of about five scanning steps. We scanned the path difference over a range of ± 3 mm (Fig. 3), around the equilibrium point. Hence the time order of the events passes from a before-after situation, where there is a defined time ordering in all reference frames to the ambiguous before-before condition and then back to an after-before situation. However, several scans like the one presented in Fig. 3 show no effects on the visibility. A similar measure with both acoustic waves traveling against each other (*after-after* condition [3]) does not show any change of the correlations either. We can add that given the distance and the uncertainty on the time of arrival, we can fix a lower bound of the speed in the laboratory frame of any hypothetical quantum influence to be $4.6 \times 10^5 c$.

Classical correlations are correlations between events; either the events have a common cause or one event has

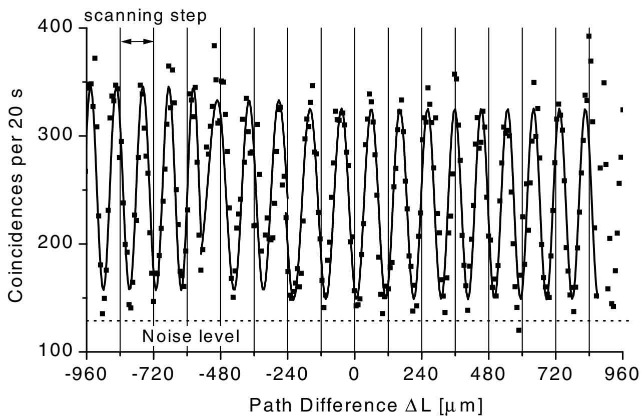

FIG. 3. Two-photon interference fringes. The total scan was done on a range of ±3 mm, but for more clarity the figure shows only a range of ±1 mm around the estimated equilibrium point. Each vertical line grid corresponds to a step of the scan. No disappearance of the correlation is observed.

a direct influence on the other(s). That is, classical correlations is a secondary concept, built upon the primary concept of event: the cause of ordinary correlations can be reduced to the cause of the events. As for quantum correlations, the violation of Bell's inequality rules out the common cause explanation, and correlations between spacelike separated events exclude influences propagating slower than the speed of light.

Multisimultaneity is an alternative model to standard quantum mechanics in which several reference frames, determined by the local physical devices and apparatuses, each define a time-ordered causality with faster than light influences (the influences being not under human control, they cannot be used for signaling). In all situations where the different components of the measuring apparatuses are at relative rest, multisimultaneity has the same prediction as quantum mechanics. However, in the intriguing situation where entangled particles are analyzed by two beam splitters in relative motion such that each one analyzes "his" particle before the other, multisimultaneity predicts that the quantum correlations disappear. Since in the reported experiment the correlations did not disappear, multisimultaneity is refuted. Recall that a model assuming that the detectors determine the relevant frames has already been refuted [11,12].

These results stress the oddness of quantum correlations. Not only are they independent of the distance, but also it seems impossible to cast them in any real time ordering. Hence one cannot 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: Quantum correlations are directly caused by the quantum state in such a way that one event cannot be considered the "cause" and the other the "effect."

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