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Quantum correlation with moving beamsplitters in relativistic configuration

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Abstract. We present a recent experiment [1] using space-like beamsplitters in motion revealing a new feature of quantum nonlocality: The correlations caused by two-particle quantum entanglement are not only independent of distance (as we already know from the conventional Bell-type experiments) but also independent of the time-ordering between the two single-photon measurements. Hence, it seems impossible to cast them in any real time ordering and maintain a causal explanation in which an earlier event influences a later one by arbitrarily fast communication.

Keywords. Quantum correlations; special relativity.

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1. Introduction

Two events are said to be correlated when the results of a measurement on one depends on the state of the other one. Classically, correlations between separated events can be explained by two different mechanisms: either both events have a common cause in the past, like all players stopping the game when the referee whistles; or one event has a direct influence on the other, e.g. a player committing a fault is censored by the referee. In both cases there is a time-ordered causal relation.

Quantum correlations, on the other hand, are of very different nature. Quantum mechanics predicts correlated outcomes in space-like separated regions for experiments using pairs of entangled particles. In that case, violation of Bell's inequality rules out the common cause of explanation [2]. Many experiments have demonstrated such quantum correlations, under several conditions [3], in perfect concordance with the quantum mechanical predictions. However, those experiments do not rule out a possible influence of one outcome on the other, but they only show that it would have to be supraluminal (without allowing faster-than-light communication). A theory, called multisimultaneity, has been developed [4], assuming the existence of a supraluminal influence. It follows the pilot-wave model of de Broglie and Bohm [5]. This theory overcomes the tensions which appear with supraluminal influences. Indeed a time-ordered causation between two space-like separated events is not relativistically covariant, as the time ordering depends on the reference frame. Therefore we have to introduce a preferred frame in which the causation process is relevant. One could imagine a unique preferred frame [6] which is relevant for all quantum measurements. If, in the preferred frame, both choices occur in a time interval short enough, the correlations would disappear as the influences would not have the time to propagate. However, experimentally this theory cannot be refuted, but only confirmed, because the speed of the influence can be arbitrarily large and is not specified by the theory.

The other possibility for a preferred frame 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 [7]. In multisimultaneity, as in the pilot-wave model, each particle emerging from a beamsplitter 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 beamsplitters 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 beamsplitters move apart, there are 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 then has 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, the nice feature is that it can be tested using the existing technology. Since it would have been very difficult to put conventional beamsplitters in motion, we used traveling acoustic waves as beamsplitters to realize a *before–before* configuration. It has been shown that the state of motion of the moving acoustic wave defines the rest frame of the beamsplitters [8]. We would like to stress that a before–before experiment using detectors in motion has already been performed confirming quantum mechanics, i.e., the correlations did not disappear [9,10].

2. Two-photon interference with frequency shift

In the Franson configuration (figure 1) [11], each photon from an energy–time entangled photon source [12] is sent to an analyzer. Each one constitutes an unbalanced interferometer, the difference between the long and short arms being much larger than the coherence length of a single photon. The main idea is that the coincident events when both photons take the short arms or both the long ones are indistinguishable because the emission time is undetermined. Hence interference between these two paths can be observed.

In our experiment we have to take care of the effects of the Doppler shift due to reflection from a moving mirror. This is equivalent to changing the frequency in one arm of the interferometers. Hence if the frequency of the incident light is ω, the frequency of the reflected light will be $\omega + \Omega_i$, while the transmitted light is not affected. The important parameter is the sum of the frequency shifts $\Omega^0 = \Omega_a + \Omega_b$.

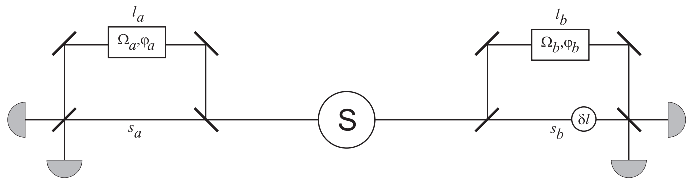

Figure 1. Franson-type Bell experiment with frequency shift.

Following closely Franson's calculations [11], but taking into account the frequency shifts and the finite bandwidth of the pump laser and of the down-converted photons as well as the bandwidth of the frequency shifter, we find, assuming Gaussian spectral distribution $\left(f(x,y) = \exp\left(-\frac{1}{2}x^2y^2\right)\right)$,

$$R = \frac{1}{2}\left[1 + V\cos\left(\Phi - \bar{\omega}_0 \Big/ 2\frac{\delta l}{c} - t\Omega^0\right)\right],$$

with

$$V = f\left(\frac{\Delta l^b}{c}, \delta\omega_0\right) f\left(\frac{\Delta l^a - \Delta l^b + \delta l}{c}, \Delta\right) f\left(\frac{l_s^a}{c} - t, \Delta\Omega_a\right) f\left(\frac{l_s^b}{c} - t, \Delta\Omega_b\right),$$

where $\Delta l^i = l_i - s_i$ is the path difference in interferometer i, $\delta l/c$ is the phase added in one interferometer, $\delta\omega_0$ is the pump bandwidth, Δ is the photon bandwidth and $\Delta\Omega_a$ the frequency shifter bandwidth. This formula contains all the usual conditions to see high-visibility interference fringes: the coherence length of the pump laser has to be greater than the path difference in one interferometer, the photons coherence length has to be greater than the difference $\Delta l^a - \Delta l^b$. Moreover, there are new conditions coming from frequency shifts. First, the bandwidth of the frequency shifter has to be much smaller than the measurement time inverse. The second condition is more subtle, even if both frequency shifters are monochromatic, when they do not add to zero, i.e., $\Omega^0 \neq 0$, the coincidence rate oscillates in time with a frequency Ω^0. Therefore if we look at the coincidence rate as usual, by integrating the coincidence counts over a long time τ (typically 10–20 s), the count rate will be averaged to 0 when $\tau \gg 1/\Omega^0$. In that case the interference fringes cannot be observed.

3. Experimental setup

The setup we used to test entanglement of the photon pairs with moving beamsplitters (figure 2), is based on previous Franson-type experiments [9], the main conceptual difference being the frequency shift in one arm of the interferometers.

3.1 *The source*

The photon pairs are created by parametric down-conversion in a recently developed highly efficient source. It is based on a waveguide integrated on a periodically poled lithium

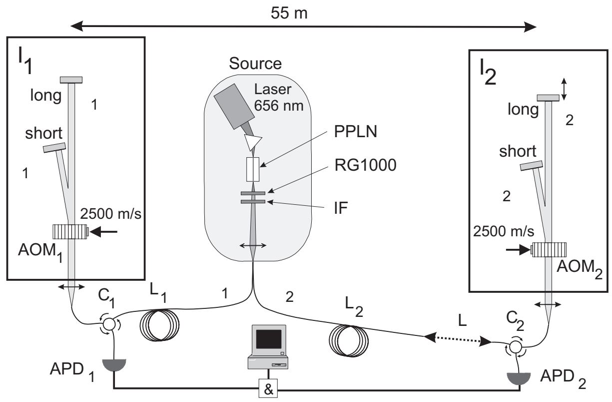

Figure 2. Schematic of the experiment. Each photon of one pair created by the PPLN waveguide is coupled into an optical fiber (L_1 and L_2). An RG1000 filter blocks the pump laser and a 11 nm interference filter (IF) narrows the photons' bandwidth. L_2 can be changed to ΔL by pulling on a fiber. Each photon is sent in an interferometer (I_1 and I_2), which uses an acousto-optic modulator (AOM) as a 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 photodiode detectors (APD). The detected signals are sent to a coincidence circuit. As the frequency shifts are compensated, the total energy ($\omega_1 + \omega_2$) when the 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.

niobate (PPLN) substrate [13]. Using a pump at around 657 nm, it generates degenerate photons at 1314 nm. We chose this wavelength as it corresponds to a transparency window in optical fibers. Hence it is possible to use this setup for long distance transmission. An RG1000 filter is placed after the waveguide to eliminate the pump light, and an additional interference filter is used to narrow down the generated photons' bandwidth. The photon pairs are coupled into a 50/50 fiber-optic beamsplitter which separates the twin photons. Violation of Bell inequality has already been demonstrated with this source [14].

3.2 *Acousto-optic modulator as a moving beamsplitter*

An acousto-optic modulator (AOM, Brimrose AMF-100-1.3–2 mm) is made of a piece of glass, in our case AMTIR (amorphous material transmitting infrared radiation), in which an acoustic wave at frequency Ω is created by a piezoelectric transducer. The transducer is driven by a 100 MHz radio-frequency (rf) driver. The refractive index of a material depends on the pressure, therefore the acoustic wave creates a periodic change of the refractive index, equivalent to a diffraction grating. If the acoustic wave is traveling rather than being stationary, it will be equivalent to a *moving* diffraction grating. This can be achieved if the AOM ends with a skew cut to damp the wave. As for a standard grating, the reflection coefficient is maximal at 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 for small angles is [15]

$$R = \frac{\pi^2}{2\lambda^2}\left(\frac{L}{\sin\theta}\right)^2 \mathscr{M} I,$$

where I is the acoustic power, $L/\sin\theta$ is the penetration of light through the wave, and $\mathscr{M}$ is a material parameter. The power was set such that the beamsplitting ratio is 50/50.

A point which gives us confidence in using an AOM [8] as a moving beamsplitter is that the reflection from 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 speed and θ the angle between the incident light wavefront 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:

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

Using $\lambda_s\nu_s = v_s$ for the sound wave and eqs (1) to (3), we found that the frequency shift induced by AOM is the same as the one induced by a mechanical grating traveling at a speed v_s. The speed of sound in AMTIR is $v_s = 2480$ m/s.

3.3 *Interferometers*

We built two bulk Michelson interferometers using AOMs instead of beamsplitters. The light is coupled out of the fiber using an APC connector to avoid back-reflection at the fiber's end. Because of the small deviation angle (about 5°) we collect only the light coming back into the input port using a fiber optical circulator. With monochromatic light, the transmission through each interferometer is about 45%. This is due to imperfect overlap of the modes. The transmission for large bandwidth photons will be reduced in the reflected arm because the deviation angle depends on the light wavelength. Hence an AOM will act as a band-pass filter for the reflected beam with a measured bandwidth of about 30 nm. To minimize these effects we will have to insure that the bandwidth of the photons is smaller by placing a spectral filter (11 nm bandwidth) after the source.

3.4 *Sychronization*

In order to observe interferences we need $\Omega^0 = 0$. Hence both frequency shifts have to be of nearly equal magnitude but of opposite signs. Therefore rf drivers need to be synchronized a fixed frequency apart such that the phase shift is of the order of the time needed to measure one interference fringe, i.e., about 150 s. This implies that the frequency difference has to be smaller than 10^{-2} Hz. This is done by using the same oscillator for both drivers.

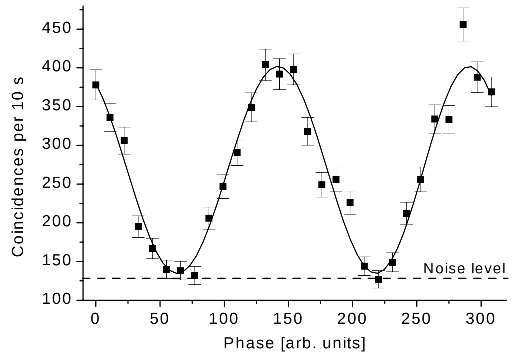

Figure 3. Two-photon interference fringes. According to a sinusoidal fit, the visibility is 97±5% after subtraction of the accidental coincidences.

Once the sychronization is correctly done and 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±5% after subtraction of the accidental coincidences (figure 3). We observed that the visibility is very sensitive to a small difference in the electric spectra of the rf signals driving the two AOMs.

4. Relativistic configuration

As we have seen, an AOM is a realization of a moving beamsplitter. We can then use our interferometers to set a Bell experiment with moving beamsplitters in order to confront quantum mechanical predictions with multisimultaneity. We need to perform the experiment in the so-called *before–before* condition. The criterion given by special relativity for the change in time ordering of two events in two reference frames counterpropagating at speed v is

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

where Δt and d are respectively the time difference and the distance between the two events in the laboratory frame [4]. This criterion is much more stringent than the space-like separation condition $|\Delta t| < d/c$. Due to the high speed of the acoustic wave (2500 m/s), a distance of 55 m between the interferometers is enough, and allows us to realize the experiment inside our building. The permitted discrepancy on the time of arrival of the photons in the AOM is then, according to (4), 1.53 ps, corresponding to a distance of 0.46 mm in air.

To observe the predicted disappearance of the correlations, the spreading of the wave-packet due to the finite bandwidth of the photons combined with the dispersion into the optical fibers has to be smaller than Δt. The coherence length of the single photons is given by the filter after the source. With a 11 nm filter the photon coherence length is about 0.14 mm. Moreover, thanks to the energy correlation, the dispersion can be almost

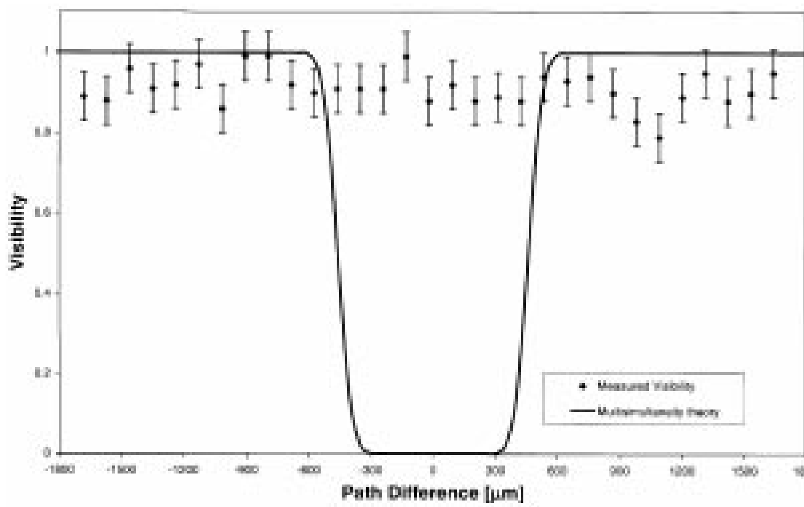

Figure 4. Visibility vs. path difference, the plain curve corresponds to the predictions of multisimultaneity theory

canceled. The requirement for the two-photon dispersion cancelation [16] is that the center frequency of the two photons is equal to the zero dispersion frequency c/λ_0 of the fibers. We measured this value on a 2 km fiber with a commercial (EG&G) apparatus 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 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 [9] corresponding to a length of 0.06 mm in air, which is much smaller than the permitted discrepancy. The total spread is given by $\sqrt{0.15^2+0.06^2}=0.152$ mm.

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 0.11 mm. Simultaneously we keep scanning the phase to observe interferences.

The theory predicts a disappearance of the correlations in the *before–before* case. That is, the visibility depending on the path-difference x would be 0 when $|x| < \Delta t$ and 1 otherwise. However, as the photons have a non-zero coherence length and are subject to spreading due to dispersion, the correlations would vanish smoothly. Figure 4 shows the measured visibility for different path differences and the expected curves according to multisimultaneity. No disappearance of the correlations is observed.

5. Conclusion

A theory assuming supraluminal influences to explain quantum correlations would lead to disappearance of the correlations. Multisimultaneity is such an alternative model to standard quantum mechanics. In all situations where the different components of the measuring apparatus are at relative rest, multisimultaneity has the same prediction as quantum mechanics. However, in the intriguing situation where entangled particles are analysed by two beamsplitters in relative motion such that each one analyses '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 [9,10]. 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 quantum correlations are directly caused by the quantum state, such that one event cannot be considered as causing the other with arbitrarily fast influence.

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