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Causality, relativity and quantum correlation experiments with moving reference frames

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Abstract. Entanglement, one of the most important features of quantum mechanics, is at the core of the famous Einstein–Bohr philosophical debate [1] and is the principal resource for quantum information processing [2]. We report on new experimental investigations of the properties of entangled photon pairs with emphasis on the tension between quantum mechanics and relativity [3,4]. Entangled photons are sent via an optical fiber network to two villages near Geneva, separated by more than 10 km where they are analyzed by interferometers [5]. The photon pair source is set as precisely as possible in the center so that the two photons arrive at the detectors within a time interval of less than 5 ps (corresponding to a path length difference of less than 1 mm). This sets a lower bound on the 'speed of quantum information' to 10^7 times the speed of light. Next, one detector is set in motion [6] so that both detectors, each in its own inertial reference frame, are first to do the measurement! The data always reproduces the quantum correlations.

Keywords. Quantum information processing; quantum communication.

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Since the famous article by Einstein, Podolsky and Rosen (EPR) in 1935 [7] 'quantum non-locality', received quite a lot of attention. They described a situation where two entangled quantum systems are measured at a distance. The correlation between the data can not be explained by local variables, as demonstrated by Bell in 1964 [8]. Recent experiments have significantly increased the spatial separation between the measured systems, making the paradoxical aspect even more striking [9,5,10]. In quantum mechanics, the EPR-Bell situation is presented as follows: The system that undergoes a measurement first, let us call it the Alice system, produces a random outcome, with probabilities determined locally by the quantum rules. Instantaneously, the state of the second system, Bob's, is reduced accordingly. The second measurement then produces outcomes following probabilities determined by this reduced state. This non-local reduction leads to the correlation between the outcomes on Alice and Bob systems. In a realist's view the correlation could be 'explained' by an action of the first measurement on the second one. This explanation is intuitive if the distance between the two detection events is time-like, i.e. one event lies in the future light cone of the other. However, if the distance between the two measurements is space-like, i.e. if none of the two events is in the future light cone of the other, this 'causal explanation' does no longer hold, besides one admits an influence of some kind that is transmitted faster than light from one side to the other. This tension between quantum mechanics and relativity has been widely studied by Shimony [3], Aharonov and

Albert [4] and Percival [11] among many others. The quantum correlations, however, can not be used to communicate information faster than light. Indeed, the data on both sides, although highly correlated, is random. There is thus no obvious conflict with special relativity. Nevertheless, it is of great interest to explore the relation between the quantum world and special relativity. So far this has been done either with Bell experiments [12,13,5,10] or with purely theoretical means [3,4,14,11]. Here we present results on two experiments that go beyond the standard tests of Bell inequality. Their objective is to explore experimentally the possible limits of quantum mechanics. Without entering the never ending dispute between the realists and positivists, we aim to test the most peculiar predictions of quantum physics and to open the road for further experimental investigations of these no-longer purely philosophical questions.

The experimental setup is similar to our Franson-type Bell-experiment presented earlier in more detail [5,15], see figure 1. A source of time-energy entangled photons is located in a Swisscom terminal in the center of Geneva. It consists of a 30 mW 655 nm diode laser with external grating pumping a $KNbO_3$ nonlinear crystal in which some 655 nm photons are spontaneously downconverted into pairs of photons around 1310 nm. The photons are then sent through the Swisscom optical fiber network to two villages, Bellevue north of Geneva and Bernex south of Geneva. The bee-line between the two villages is of 10.6 km. There, the photons are analyzed by two identically imbalanced fiber optic Michelson interferometers (with Faraday mirrors to compensate for the fiber birefringence [15]). The use of optical circulators at the input ports provides access to both outputs of each interferometer. The photon counters are liquid nitrogen cooled, passively quenched Ge avalanche photodiodes. All detections trigger laser pulses that are sent to the coincidence electronics through another optical fibre. A time-to-amplitude converter with single channel analyzer selects the events with the right time interval (using 600 ps coincidence windows), corresponding to the two interfering possibilities when the photons take either both the short or both the long arm of their interferometer. We obtain typically 2 kcts/s single count rates

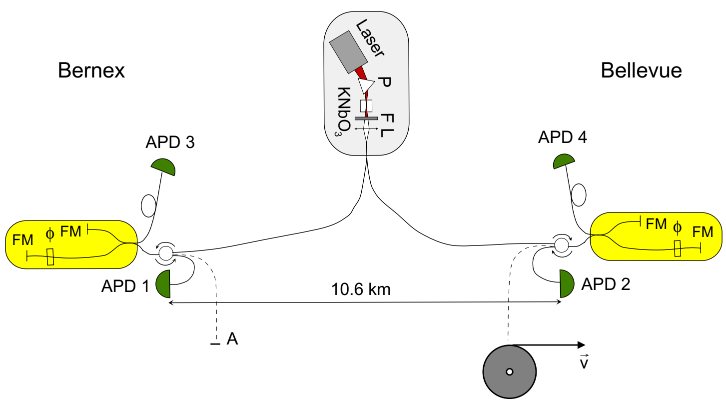

Figure 1. Schematic of the experiments that consist essentially of a photon pair source in Geneva and two analyzers in Bellevue and Bernex, respectively, seperated by 10.6 km. In the first experiment, the optical path lengths from the source ($KNbO_3$-crystal) to the two photon counters APD1 and APD2 are exactly the same. In the second experiment, they are replaced by an absorbing surface A and a rotating wheel, again both at equal distances from the source.

and a mean value of about 3 coincidences per second (incl. 2 accidentals). This is significantly lower than in our previous experiments [15] because of the optical filters that we had to use (see below) which reduce the spectral width of the downconverted photons.

The cases when the photons either both take the short arm of their interferometers, or both take the long arm, are indistinguishable (provided the coherence of the pump laser is larger than the interferometers' imbalancement) leading to interference according to Feynman's criterion. Indeed, the quantum correlations are a consequence of interference in the coincidence count rates that depend on the sum of the phases in both interferometers. The correlations can be measured between any pair of outputs, one of each interferometer. The interferometers are temperature controlled. The one in Bernex is kept at a constant temperature of 31°C, while the temperature of the interferometer in Bellevue is scanned between 30.5 and 37.5°C. This produces a variation of the phase of about $10 \cdot 2\pi$. We can thus continuously measure the correlation as a function of the phase. The interferometers' imbalancement was measured to be equal when the temperature is $34\,^\circ$C.

When two events are space-like separated there always exists a reference frame in which, according to special relativity, they are simultaneous. However, in general, this reference frame differs from the natural reference frame of the experiments in which the source, the analyzers and the detectors are at rest. The aim of our first experiment is to equilibrate the lengths and the chromatic dispersions of both fiber links from the source to Bernex and to Bellevue so that the detection events are simultaneous in the natural Geneva reference frame. More precisely, we equilibrate the paths to the detectors, assuming that the 'choice device' is the detector. This is the most natural choice since it is there, where the irreversible decoherence (the transition from the quantum to the classical) happens. Particularly, we assume that the transition happens in the first microns of the detector, where the absorption takes place. To adjust roughly the distances we add 1.5 km of optical fiber on a spool on the link to Bellevue. Furthermore we add about 500 meters of dispersion shifted fiber on the link to Bernex, this is necessary because the chromatic dispersion of this link is higher (dispersion shifted fibers have relatively high negative dispersion around 1300 nm). Finally, each fiber link measures in total about 10 km and has about 9 dB losses. Next, the fiber lengths are measured with a home made OTDR (optical time domain reflectometer) with a precision of a few cm. Short fiber pigtails are used for this adjustment. In a further step, we use another home made (but now commercial) low coherence interferometer [16] with 100 μm resolution (using a LED with a 2 nm FWHM interference filter). Fine tuning is realized by pulling on a 2 meter long fiber on a rail with a micrometer-screw (optical fibers have a 1% elasticity domain).

The dispersion induced spreading of the wavepackets may easily be larger than the achievable precision of the positioning. To limit the spreading we take advantage of the 2-photon chromatic dispersion cancellation phenomena [17,18]: if the central wavelength of the downconverted photons is precisely at the (average) zero chromatic dispersion wavelength of the two fibers, then, in the domain where chromatic dispersion varies linearly, both photons undergo exactly the same delay. We thus measured accurately the chromatic dispersion of the fiber links and found the zero chromatic dispersion wavelength with a precision of ± 0.2 nm. This uncertainty determines together with non-linear terms of the chromatic dispersion the width of the 2-photon wave-packet at the detectors. Reducing the bandwidth of the downconverted photon with a 10 nm filter, we estimate that the resulting spread is below 5 ps (a detailed analysis will be published elsewhere [19]). The reduction of the bandwidth, however, goes with a reduction of the count rates to the values given above.

Due to thermal expansion, the optical lengths between Geneva and each of the villages changes by several mm over day. We observed that Bernex is drifting further away during the daytime, since this link is more exposed to temperature variations. The drift proves to be monotonic, in one direction during the day and in the other one during the night. So we aligned the paths taking in account the daily drift such that the optical distances from the source to the two interferometers will be perfectly equal some time later. During these few hours we continuously record the 2-photon interference fringes, varying uniformly the phase of the Bellevue interferometer. After an acquisition we confirm with a second measurement that the path lengths really passed through the equilibrium point. Many interferograms were collected over various day and night periods and measurement times. Figure 2 displays typical data taken over 6 hours while the optical link to Bernex lengthened by 2 mm with respect to the one to Bellevue. Inevitably, the curves show high statistical fluctuations due to the low count rate. In spite of this, one can state that the visibilitiy of the two photon interferogram remains constant. Especially, a reduced visibility over a scan span of 1 mm (corresponding to 5 ps) should easily be noticed. After substraction of the

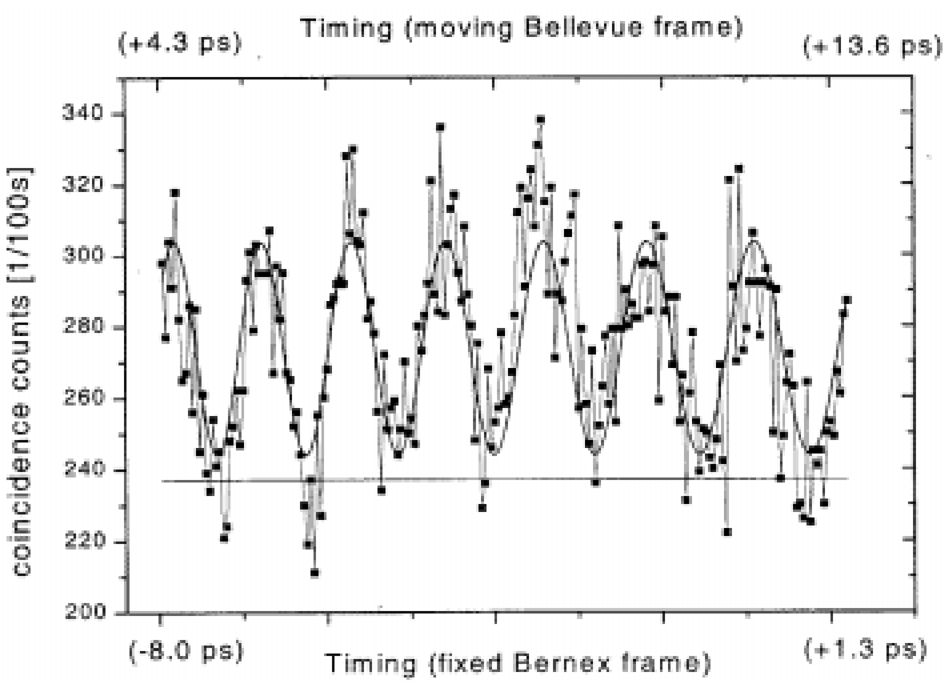

Figure 2. 2-photon interference fringes measured over 6 hours, each data point corresponds to a time interval of 100 s. The difference of the optical path lengths is varying from -8 to $+1.3$ ps. Negative values mean that the detections occurs first in Bernex in the fixed Geneva–Bernex reference frame. In the moving Bellevue reference frame the detections happen first in Bellevue over the entire scan range, as indicated on the upper time scale. Despite this different time ordering no reduced visibility is observed.

237±5 cts/100 s accidental coincidences, the fit of figure 2 shows a constant fringe visibility of 83%, large enough for a violation of Bell's inequality. This demonstrates quantum correlation measurements simultaneous in the natural reference frame and we can set a conservative, nevertheless impressive lower bound on the speed of any hypothetical quantum influence (in the Geneva reference frame):

$$\frac{10.6\ \mathrm{km}}{5\ \mathrm{ps}} \approx 2 \cdot 10^{15}\ \frac{m}{s} = \frac{2}{3} 10^{7}\ c, \tag{1}$$

where c denotes the speed of light. Removing the 10 nm filter limiting the bandwidth of the photon pairs, one obtains less noisy curves that nicely demonstrate constant fringe visibility. In this case however, the lower bound given above must be reduced by an order of magnitude, due to the dispersion induced spreading of the photons.

Let us emphasize again that the above bound on the speed of 'quantum information' (quantum state preparation) is not in conflict with relativity. What can be said is that Alice can predict with certainty the quantum state of a photon 10 km away which was still in a completely mixed state some ps before. Whether this implies the transmission of some kind of information (or influence) is a matter of debate and models [20]. In this respect the recent progress on evaluating the cost of classical communication for the simulation of quantum correlation is interesting [21,22]: to simulate our experiment with classical communication one would not only need supraluminal communication, but the extreme nonrealistic speed of 10 million time the speed of light.

The aim of our second experiment is to investigate a situation were both Alice and Bob, each in their own natural reference frame, do perform the measurement before the other (or both after the other). It has been argued that in such a scenario the correlation might break down [6]. Indeed, one can imagine that in this situation each particle independently produces a random outcome (or at least, that the correlations drop below the Bell limit). According to special relativity, such a frame dependent chronology requires that Alice and Bob are in relative motion with a speed larger than [6]

$$v \geq \frac{\delta t c^2}{L} \approx \frac{5\ \mathrm{ps} \cdot c^2}{10.6\ \mathrm{km}} \approx 42\ \frac{m}{s}, \tag{2}$$

where δt is the uncertainty of the equilibration of the paths which is determined by the pulse spreading ($\leq$ 5 ps). Clearly, it is unpractical to speed up the entire interferometer plus liquid nitrogen cooled photon counters. We argue that this is not necessary and that actually a much simpler configuration suffices. We assume again that choice device is the detector, therefore only the detector has to be in motion. Moreover, the essential physics of a detector being the irreversible absorption of photons, we argue that it is not necessary to collect the data of the detector. The quantum correlation and its hypothetical breakdown can be measured using the other output ports of the interferometers, paying attention that the detectors (APD 3 and APD 4) attached to these second ports are further away. Further, we argue that there is no fundamental difference between a photon absorbed by the Ge layer followed by an inactivated detector and a photon absorbed by any black surface. The argument here is that the relevant physics happens in the absorption, not in the electronics (and even less in the human observer). Hence, we replace one of Alice's detector (in Bellevue) by the black painted edge of a fast rotating wheel (a 20 cm diameter aluminium disk of 1 cm thickness directly driven by a brushless 250 W DC motor). The wheel turns vertically at 10000 rpm leading to a tangent speed of 105 m/s. It is oriented with a compass to make it run away or towards the other observer at Bernex. The circular motion provides thus a good approximation to a linear one defining the inertial reference frame, since during the 50 μs time of flight of the photon from the source, the wheel's edge moves only by about 5 mm. In addition to simplicity the identification of the 'choice device' to the edge of the wheel has the advantage that the choice device always moves in the same direction.

In all cases our experimental results are in good agreement with the quantum mechanical predictions and no breakdown of the quantum correlations was observed. Actually, the 2-photon fringes displayed in figure 2 were collected while the wheel was rotating, such that both measurements where 'before the other' (in their own inertial reference frame) over almost the entire scan range. We would like to mention that with the detectors as 'choice device' a breakdown of the correlations would allow to exploit 'non-locality' for supraluminal communication by slightly adapting the setup [19]. We also measured interferograms corresponding to the 'after-after' configuration by inversing the rotation of the wheel and with the wheel at rest, again with no evidence for a breakdown of the correlations.

It is a great time for quantum physics. Both its foundations and its potential applications are deeply explored by a growing community of physicists, mathematicians, computer scientists and philosophers. Entanglement between distant systems is the major resource for quantum communication and is at the core of the uneasiness many people face with the quantum world. We explored experimentally some of the most counter intuitive predictions of quantum theory, stressing the tension with relativity. Our results fully support the quantum predictions, re-enforcing our confidence in the possibility to base future understanding of our world and future technology on quantum principles. It also contributes to the renewed interest for experimental challenges to the interpretation of quantum mechanics and is relevant for the realist-positivist debate. 'Experimental metaphysics' questions [23] like 'what about the concept of states?', 'the concept of causalities?' will have to be (re)considered taking into account the results presented in this letter. For example, our results make it more difficult to view the 'projection postulate' as a compact description of a real physical phenomenon [24,25]. Actually, it seems that there are only three possibilities left. First, our argument in favor of the detector as 'choice device' may be wrong. To check this, further experiments are planned, in particular with moving beam-splitters [6]. Second, some physicists have argued that reduction of quantum states happen in some privileged frame [14], a hypothesis that deserves to be elaborated [11]. Finally, a many-universe view might be considered [26].

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