Non-local two-photon correlations using interferometers physically separated by 35 meters

W. Tittel, J. Brendel, T. Herzog, H. Zbinden and N. Gisin
University of Geneva, Group of Applied Physics, 20, Rue de l’Ecole de Medecine, CH-1211 Geneva 4, Switzerland
e-mail: wolfgang.tittel@physics.unige.ch
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Abstract

An experimental demonstration of quantum-correlations is presented. Energy and time entangled photons at wavelengths of 704 and 1310 nm are produced by parametric downconversion in KNbO3 and are sent through optical fibers into a bulk-optical (704 nm) and an all-fiber Michelson-interferometer (1310 nm), respectively. The two interferometers are located 35 meters aside from one another. Using Faraday-mirrors in the fiber-interferometer, all birefringence effects in the fibers are automatically compensated. We obtained two-photon fringe visibilities of up to 95 % from which one can project a violation of Bell’s inequality by 8 standard deviations. The good performance and the auto-aligning feature of Faraday-mirror interferometers show their potential for a future test of Bell’s inequalities in order to examine quantum-correlations over long distances.

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Tests of the well known Bell-inequality [1], which prescribes the upper limit for correlations between entangled particles under the assumption of local hidden variables theories (LHVT) [2], have been made for about twenty years now. All tests are based on four parts: first, the source, creating entangled particles. Next, the two independent measuring devices, each one examining one of the particles for the correlated feature and ascribing a binary value to the outcome (Bernoulli-Experiment). Finally the electronics, putting together the results and giving thus evidence to the nonlocal correlations (see Fig. 1). Polarization [3–8], momentum [9], as well as energy and time [10–12] entangled photons have been used to show violations of the inequality and thus confirm the quantum-mechanical (QM) predictions. Even a separation of the different experimental locations by 4.3 km of coiled standard optical fiber corresponding to a physical distance of a few meters (therefore being rather time- than spacelike) did not affect the strong correlations [12]. However, giving up local realism has such far reaching conceptual implications that further experimental investigations to close remaining loopholes for LHVT are desirable. Moreover, the exploration of potential applications of quantum entanglement like quantum-cryptography [13], teleportation [14] or more generally, processing of quantum information requires solid experimental grounds.

To date, all tests of the Bell-inequality are based on assumptions, which, although seeming reasonable, provide the means to criticize them [15]. The experiments can be improved along the following lines. First, there is the so-called detection loophole: the detected pairs of particles could constitute a nonrepresentative sample. Second, the locations of the measuring devices should be spacelike separated in order to guarantee Einstein locality - no information on the analyzer setting on one side can propagate to the other side before both particles are detected. Hence, the settings of the two measuring devices have to be randomly selected after the particles have left the source. Third, the physical distance between the source and the analyzers should be increased, in order to test the QM predictions that the correlations do not decrease with distance. Fourth, massive particles should be investigated, as almost all experiments used massless photons [16]. In the present work, the first and the fourth point are not touched. Obviously, the two other points are closely related: to overcome the second one, the third one has to be mastered. The easiest way to achieve this, is to use optical fibers and photons at 1310 nm wavelength in order to keep dispersive effects and losses small.

In this letter, we present a Franson-type experiment [17] based on energy and time entangled photons at center wavelengths of 704 and 1310 nm. Both photons are analyzed using Michelson-interferometers - the photon of the lower wavelength with a bulk-optical, the infrared photon with a fiber-optical one. In general, polarization mode dispersion (PMD) has to be compensated by polarization controlling elements when working with fiber-optical interferometers. Using Faraday mirrors instead of regular mirrors in the fiber interferometer we achieve an almost perfect and automatic compensation. Source and measuring devices are located in three different laboratories. The source is placed in the central lab, the 704 nm photon analyzer five meters aside in the lab next door and the 1310 nm photon analyzer in a third lab, located about 30 meters away in opposite direction down the corridor.

The Bell-inequality can be written [18] as a combination of four correlation measurements with different analyzer settings a and b (e.g. interferometric phase shift or orientation of a polarizer)

\[
S = |E(a,b) - E(a',b')| + E(a',b) + E(a',b') \leq 2
\] (1)
and the correlation coefficient [5]

\[ E(a, b) := \frac{R_{++}(a, b) - R_{+-}(a, b) - R_{-+}(a, b) + R_{--}(a, b)}{R_{++}(a, b) + R_{+-}(a, b) + R_{-+}(a, b) + R_{--}(a, b)} \]  

(2)

\( R_{+-} \) being e.g. the coincidence count rate between the + labeled detector at interferometer 1 and the - labeled one at interferometer 2.

In our experiment two photons entangled in energy and time are directed each one into an equally unbalanced interferometer. Since the path difference in each interferometer is much greater than the coherence length of the single photons, no second order interference can be observed. However, due to the entanglement, the possibility for the two photons to choose equivalent outputs can be affected by changing the phase-difference in either interferometer (δ₁ or δ₂ resp.). The quantum physical approach describes this effect as fourth order interference between the probability-amplitudes corresponding to the two possibilities, whether the correlated photons choose both the short arms or both the long ones to traverse the interferometers. Due to the two remaining possibilities - the photons choose different arms - the visibility is limited to 50 %. However, using a fast coincidence technique [19], the latter events can be excluded from registration thus increasing the maximum visibility to 100 % and leading to the coincidence probability [10]

\[ P_{ij}(\delta_1, \delta_2) = \frac{1}{8} (1 + ijV \cos(\delta_1 + \delta_2)), \]

(3)

where \( i, j = \pm 1 \) and the visibility factor V describes experimental deviations from the maximum value V = 1. Assuming detection of a representative sample of all photon pairs, the coincidence count rate \( R_{ij} \) is proportional to \( P_{ij} \)

\[ R_{ij}(\delta_1, \delta_2) \propto (1 + ijV \cos(\delta_1 + \delta_2)). \]

(4)

Evaluating the correlation function (2) with eq. (4) leads to

\[ E(\delta_1, \delta_2) = V \cos(\delta_1 + \delta_2). \]

(5)

Using the settings \( \delta_1 = \pi/4, \delta'_1 = -\pi/4, \delta_2 = 0, \) and \( \delta'_2 = \pi/2, \) eq. (1) yields

\[ S = V2\sqrt{2} \leq 2 \]

(6)

Therefore a violation of the Bell-inequality requires observing a sinusoidal correlation function with visibility above \( 1/\sqrt{2} \approx 71\% \).

The schematic setup of the experiment is given in Fig. 2. Light from a single-line argon laser (140 mW at 458 nm) passes through a filter (Schott; BG 39) to separate out the plasma luminescence and is focused (f = 40 cm) into a KNbO₃-crystal, a biaxial crystal showing strong nonlinear effects [20]. Tuning the crystal temperature to 157.3 C, collinear type-I phasematching for photons at 704 and 1310 nm is obtained for the A-cut crystal. Due to the noncritical phasematching conditions, the single photons exhibit rather small bandwidths of about 7 nm. Behind the crystal, the pump is separated out by a polarizer while the passing downconverted photons are launched into a standard fiber coupler. This coupler, designed to be a 3 dB (50 %) coupler at 1310 nm provides uneven transmission.
ratios for the two output arms at 704 nm. 40% of the incoming photons are directed into the arm chosen to be the “visible” one, 3.5% into the “infrared” arm and the rest is absorbed. Therefore not all of the pairs are split. Including additional 75% losses in a fiber-connection (FC) between the coupler and a fiber that guides only one mode at 704 nm, only 5% of the created photon pairs finally exit the source by different output fibers.

Having passed 50 m single mode fiber, the photons at the lower wavelength (704 nm) are directed into a Michelson-interferometer (interferometer 1) which is located 5 m aside from the source. A microscope-objective (MO; 40x) collimates the light at the input of the bulk-optical analyzer. The path-length difference, about 20 cm, is matched to the second, the fiber-optical interferometer (interferometer 2). This small value compared to the coherence length of the laser is chosen to keep phase-variations caused by temperature fluctuations or mechanical instabilities as small as possible. To change the phase-difference of interferometer 1, the mirror M1 can be moved using a translation stage which is driven by a computer-controlled micro-step-motor. At the output of the interferometer, the photons are focused into the multimode pigtail of a silicon single-photon counting module (EG&G; SPCM-AQ). To ensure high visibility, a pinhole separating out only a single fringe is placed before the collecting lens. Since the probability for a silicon detector to detect an infrared photon is close to zero, all frequency filtering to block remaining photons at 1310 nm can be neglected.

The analyzer for the 1310 nm photons, a fiber-optical Michelson-interferometer (interferometer 2), is located 30 m away from the source and connected by 60 m of standard telecom fiber. The path-length difference is equivalent to 20 cm in air (13 cm in glass or 0.7 nsec time-difference) and can be changed by a computer-driven phase-modulator (PM) - 1.5 m of fiber wrapped around a cylindrical piezotube. Instead of ordinary mirrors, we use so-called Faraday-mirrors (FM), a 45° Faraday rotator glued in front of a conventional mirror. These mirrors ensure that a photon, injected in any arbitrary polarization state into one of the interferometric arms will always come back exactly orthogonally polarized regardless any birefringence effects in the fibers. Hence, all PMD is automatically compensated, no polarization alignment is required any more. The recently reported visibility of 99.84% for a 23 km long interferometer used for quantum-cryptography [21] demonstrates the ability of Faraday-mirrors to overcome any reduction of visibility due to PMD. The output arm of the fiber-interferometer is connected to a single-photon counter, a passively quenched germanium avalanche photodiode (Ge-APD; Siemens SRD00514H) operated in Geiger mode at 77 K. Since the detection-time jitter has to be smaller than the difference between traveling times along the two interferometric arms, the APD is biased 0.7 V above breakdown (about 23.1 V), leading to a jitter of 200 ps FWHM, a detectivity of 17% and dark-counts of about 180 kHz. Due to the poor detectivity of the Ge-APD for visible photons, frequency filtering can again be ignored.

Apart from monitoring the single count rates, the signals from the single-photon detectors are fed into a time to pulse height converter (TPHC; EG&G Ortec 457) in order to manifest the correlations between the two independent Bernoulli-experiments. We use the silicon detector (the detector with the lower count rate) to start the TPHC and the germanium detector to stop it. A window discriminator permits to count coincidences within a 350 ps intervall which is matched to the arrival time of two photons having passed equivalent paths (either short-short or long-long). If the photons of a pair choose different paths (short-long or long-short) they arrive with an additional time-delay of 0.7 ns and are thus excluded from
registration. Therefore photon-pair detection is limited to the interfering processes only.

Figure 3 shows a plot of the coincidence counts we obtained during intervals of two seconds as a function of the displacement of M1 in the bulk interferometer. Accidental coincidences, about 33 Hz, are calculated for each measured point as the product of the single count rates per second and the width of the coincidence-window. They have already been subtracted. The single count rates remained constant at 250 kHz (including 60 Hz dark) for the silicon and 380 kHz for the germanium detector (including 180 kHz dark). Fitting the experimental data by a sinusoidal curve, we find a visibility of 95.7 %±3.15 %. Comparable results for a change of the path-length difference in the fiber-interferometer have been obtained, too. Our experimental setup allows to observe only one output of each analyzer. Hence, only one of the four coincidence functions in eq. (4), requested to calculate the correlation function (eq. (5)), can be detected. From symmetry considerations, it is reasonable to assume that the measurement of the 3 other coincidence functions would show the same visibility. Assuming this, we can deduce a violation of the Bell-inequality by 8 standard deviations [22].

Apart from problems with thermal stability, deviation from the maximum theoretical value for visibility of 100 % is mainly caused by the mismatch of the spatial modes in the bulk interferometer. Due to the birefringence-compensating effect of the Faraday-mirrors and chromatic dispersion close to zero, originating from the small single-photon bandwidth, contributions by the fiber interferometer are negligible.

In conclusion, strong quantum correlations over 35 meters have been observed. Under the above made assumptions of symmetry, the obtained fringe visibilities yield significant violations of the Bell-inequality. Using Faraday-mirrors in the fiber interferometer, all polarization control can be disregarded. This is a major advantage compared to already existing schemes using optical fibers. Employing two 2-output auto-aligning interferometers with improved thermal stability and creating both entangled photons at telecom wavelength of 1310 nm will implement a long distance Bell-experiment with tens of kilometers of spatial separation between the source and each of the measuring devices. This in turn will open the possibility to test quantum-mechanics with truly random settings obeying Einstein locality or more general, will lay grounds for further processing of quantum information.

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[22] To determine the visibility corresponding to the measured data, we apply a least squares fit ($\chi^2$-test), assuming the sinusoidal function (1) with V as the free parameter. The reliability of the best fit can be found by looking at the tolerated variation of the fitted parameters in order to keep the $\chi^2$ value smaller than a certain limit. This threshold, depending on the number of measured data and the desired confidence level (as common in statistics, we choose 0.95) can be found in tables. Thus, the probability that our data are corresponding to a sinusoidal function with a visibility of $81.6 \pm 1.1\%$ is 0.95.
FIG. 1. Principle setup to test the Bell-inequality. The entangled particles, created by a two-particle source, are separated and each one sent to an analyzer. Each measuring device performs a Bernoulli-experiment with binary valued output depending on the correlated feature. The results - in our case only the +1 labeled events - are put together, giving thus evidence to the nonlocal correlations.
FIG. 2. Experimental setup of the Franson-type test, see text for detailed description.
FIG. 3. Net coincidence counts per 2 sec. as a function of path-length difference in the bulk-interferometer (displacement M1). Best fit with a sinusoidal function yields a visibility of $95.7 \% \pm 3.15 \%$. 