Experimental demonstration of quantum correlations over more than 10 km

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Energy and time entangled photons at a wavelength of 1310 nm are produced by parametric down-conversion in a $KNbO_3$ crystal and are sent into all-fiber interferometers using a telecommunications fiber network. The two interferometers of this Franson-type test of the Bell inequality are located 10.9 km apart from one another. Two-photon fringe visibilities of up to 81.6% are obtained. These strong nonlocal correlations support the nonlocal predictions of quantum mechanics and provide evidence that entanglement between photons can be maintained over long distances. [S1050-2947(98)02705-X]

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Since the foundation of quantum mechanics, the often counterintuitive predictions of the theory have continued to puzzle physicists. The most peculiar aspect is entanglement, whereby, for example, a two-particle system is in a pure state, but each particle separately is in a complete mixture. Such entanglement leads to predictions for correlation measurements that violate the well-known Bell inequalities [1] and thus cannot be explained by local-hidden-variable theories. Polarization [2,3], position and momentum [4], as well as energy and time [5–7] entangled photons have been used to show violations of these inequalities and therefore confirm the strong correlations predicted by quantum mechanics. Nevertheless, the nonlocal collapse of the wave function by a ''spooky action at a distance'' [8] is still a subject for investigation [9].

In this paper we present an experiment on entangled pairs of photons physically separated by more than 10 km with the source roughly at the center. This corresponds to an increased distance by about three orders of magnitude over all previous experiments, including the one by Tapster *et al.* [7]. Our experiment took advantage of already installed optical fibers used for modern optical telecommunications. The attenuation in such fibers has been drastically improved over the past two decades, from several decibels per meter down to 0.35 dB per kilometer. Chromatic dispersion, another potentially limiting phenomenon for our experiment, has also been optimized for telecommunications purposes. Standard fibers have zero chromatic dispersion at 1310 nm. However, the use of telecommunications fibers has a drawback: photon counters at telecommunications wavelengths are relatively inefficient and noisy. Nevertheless, the experimental results clearly indicate that the strong quantum correlations can be maintained over such large distances.

The experimental fact that quantum correlations are maintained over long distances is interesting for fundamental physics as well as for potential applications. Among the latter, the most promising one is quantum cryptography [10]. More futuristic applications include dense coding [11], quantum teleportation, [12,30], and, more generally, quantum networks and other quantum information processing. All these applications require that the quantum systems (qubits) are

protected from environment-induced decoherence. In this respect, the present results are very encouraging, at least for photon pairs in optical fibers. To conclude this introduction, let us mention two of the fundamental issues. First there is the local-hidden-variable program. It seems clear that if there are no hidden variables after 10 m, there are also none after 10 km. Since our experiments improve the physical distance at the cost of higher losses, less efficient and more noisy detectors, it is not a better test of local hidden variables. However, it opens the route for an experiment in which the settings of the analyzers can be changed during the flight of the particles and therefore could close the locality loophole [13]. Such an experiment has already been made [3]; however, the switching was not really random [14]. A second fundamental issue is environment-induced decoherence [15] and ''spontaneous collapses'' [16]. The main effect of decoherence is to spread quantum correlations between the two photons of our experiment into a formidable entanglement between the photons and the environment. Since the correlations are not really broken but merely hidden, the coherence can sometimes be rebuilt as in spin echoes [17] or, in an example closer to our experiment, using Faraday mirrors to reflect light from the end of an optical fiber [18]. In contrast, the main effect of spontaneous collapses would be an irreversible destruction of the coherence [19]. Whether this requires a modification of the standard quantum dynamics is controversial [20]. Hopefully, developments following ours will lead to experimental tests [21].

In our Franson-type experiment [22] each one of the two entangled photons is directed into an unbalanced interferometer. The physical distance between these two devices is about 10 km (the shortest distance between the source and an analyzer is 4.5 km). Since the path-length difference of the interferometers, exactly the same for both of them, is much greater than the coherence length of the single photons, no second-order interference (i.e., no single-photon interference) can be observed. However, due to the entanglement, the possibility of the two photons choosing particular outputs can be affected by changing the phase difference in either interferometer (δ_1 or δ_2 respectively). This effect is described as fourth order interference (i.e., two-photon interferences) between the probability amplitudes corresponding to two possibilities: The correlated photons choose both short arms or both long arms through the interferometers. Due to

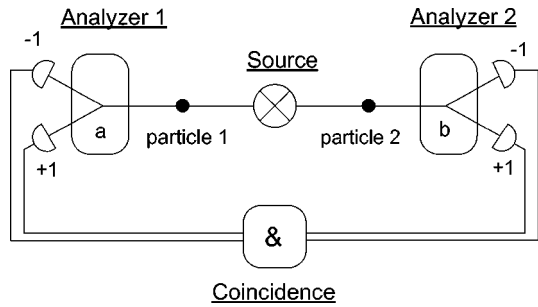*Electronic address: wolfgang.tittel@physics.unige.ch

FIG. 1. Principle of the setup to test nonlocal correlations. The entangled particles, created by a two-particle source, are separated and each one is sent to an analyzer, matched to the correlated feature (in our case energy-time entanglement and interferometers). Each measuring device, characterized by a setting parameter (*a* and *b*, respectively), performs a Bernoulli experiment with binary valued output. The results are compared, thus giving evidence to the nonlocal correlations.

the two remaining possibilities, the photons choosing different arms, the visibility is limited to 50%. However, using a fast coincidence technique [23], the latter events can be excluded from registration, thus increasing the maximum visibility up to 100% and leading to the normalized coincidence probability [5]

$$P_{i,j} := \frac{1}{4}\left\{ 1 + ijV \exp\left[-\left(\frac{\lambda(\delta_1 - \delta_2)}{2\pi L_c} \right)^2 \right] \cos(\delta_1 + \delta_2) \right\},$$
(1)

where $i, j = \pm 1$ and P_{+-} is, e.g., the coincidence probability between the detector labeled $+$ at interferometer 1 and the one labeled $-$ at interferometer 2 (see Fig. 1). Experimental deviations from the maximum visibility of 1 are described by the visibility factor V. Unequal path-length differences in both interferometers $\delta_1 - \delta_2 \neq 0$ increase the possibility to differentiate between the long-long and short-short paths (by looking at the differences in photon arrival time) and hence reduce the visibility. Therefore, the interferogram will always show an envelope representing the single-photon coherence length L_c.

The schematic setup of the experiment is given in Fig. 2. Light from a single longitudinal mode laser diode (RLT6515G; 8 mW at 655.7 nm) passes through a dispersion prism P to separate out the residual infrared fluorescence light and is focused into a KNbO$_3$ crystal. The crystal is oriented to ensure degenerate collinear type-I phase matching for signal and idler photons at 1310 nm. Due to these phase-matching conditions, the single photons exhibit rather large bandwidths of about 90 nm full width at half maximum (FWHM). Behind the crystal, the pump is separated out by a filter F (RG 1000) while the passing down-converted photons are focused (lens L) into one input port of a standard 3-dB fiber coupler. Therefore, half of the pairs are split and exit the source by different output fibers. In contrast to previous experiments, the whole source including stabilization of laser current and temperature is of much smaller dimensions (a box of about $40 \times 45 \times 15$ cm^3) and hence can easily be used outside the laboratory. In our experiment, the two-photon source is placed at a telecommunications station near
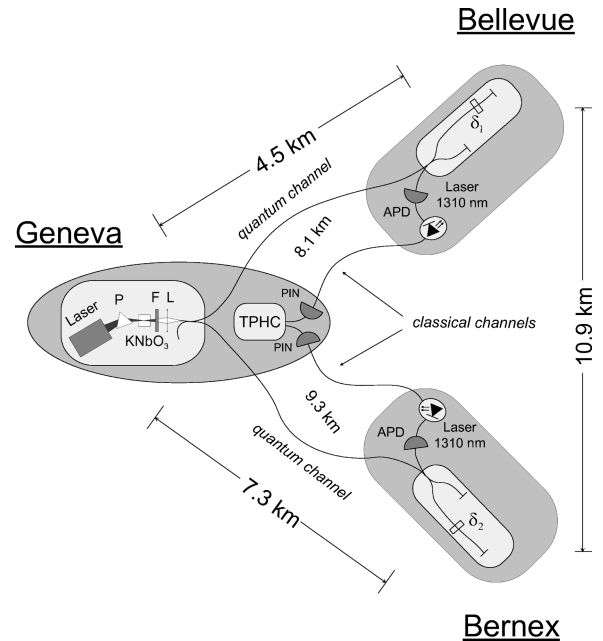

FIG. 2. Experimental setup. See the text for a detailed description.

Geneva downtown. One of the correlated photons travels through 8.1 km of installed standard telecommunications fiber to an analyzer that is located in a second station in Bellevue, a little village 4.5 km north of Geneva. Losses are about 5.6 dB. Using another installed fiber of 9.3 km, we send the other photon to a second analyzer, situated in a third station in Bernex, another little village about 7.3 km southwest of Geneva and 10.9 km from Bellevue. Absorption in this fiber is around 4.9 dB, leading to overall losses in coincidences of about a factor of 10. Since the bandwidth of the single photons is rather large, we have to consider chromatic dispersion effects in the connecting fibers. From measured differential group delays we calculate the introduced time jitter at a pump wavelength of 655.7 nm to be about 400 ps FWHM.

The two analyzers consist of all-fiber optical Michelson interferometers made of standard 3-dB fiber couplers with chemically deposited end mirrors. The optical path-length differences (20 cm of optical fiber or a 1-ns time difference) are equal in both interferometers. To ensure maximum visibility, birefringence in the fibers forming the interferometers has to be avoided. This can be attained either by compensating all birefringence effects using Faraday mirrors [18,24] or by avoiding birefringence at all. In this experiment we aimed to achieve the latter. To do so, we placed the interferometers straight and without stress into copper tubes. The temperature of the tubes can be varied in order to change and control the phase difference of the interferometers. To detect the photons, we use passively quenched germanium avalanche photodiodes (APD) (NEC NDL5131P1) operated in Geiger mode at 77 K. They are biased around 0.4 V above breakdown, leading to a detection-time jitter of 200 ps FWHM, an efficiency of about 15%, and dark counts of 100 and 110 kHz each. Each single-photon detector triggers a 1310-nm laser emitting 1-ns pulses. The (now classical) optical signals are transmitted back to Geneva using additional fibers and are detected by conventional *p-i-n* photodiodes. The overall
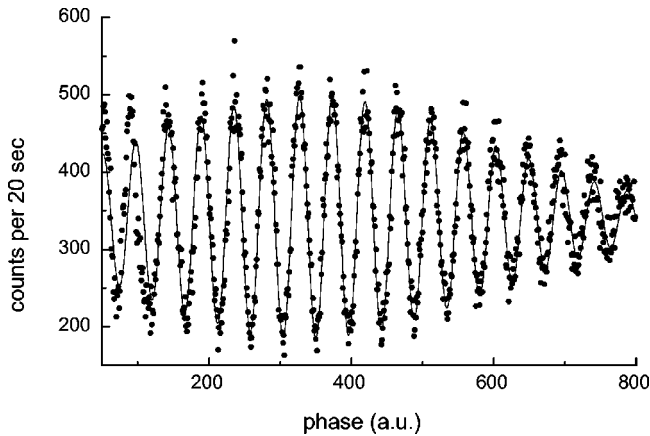
FIG. 3. Net coincidence counts per 20 sec as a function of path-length difference in the Bernex interferometer. A best fit with a sinusoidal function yields a visibility of $(81.6 \pm 1.1)\%$. From the envelope of the interferogram, we calculate a single-photon coherence length around 10.2 μm (equivalent to a bandwidth of about 90 nm FWHM).

time jitter is about 450 ps FWHM and permits one to differentiate between photons having traveled along different interferometer arms. The signals from the p-i-n photodiodes trigger a time to pulse height converter (TPHC) (EG&G Ortec 457), which is placed next to the source in Geneva. A window discriminator counts coincidences within a 400 psec interval that is matched to the arrival time of the two correlated photons having passed equivalent paths in the interferometers (either short-short or long-long). Therefore, photon-pair detection is limited to the interfering processes only.

We monitored the count rates as a function of phase differences δ_1, δ_2 in both interferometers. No phase-dependent variation of the single count rates could be observed. They remained constant at about 164 and 167 kHz (including 100- and 110-kHz dark counts) for each detector. Figure 3 shows a plot of the coincidence counts we obtained during intervals of 20 sec as a function of the temperature-caused phase change in the interferometer in Bernex. Applying a Fourier transform to these data, we find no more than one frequency exceeding the noise floor, hence confirming the hypothesis of the sinusoidal function [Eq. (1)]. Fitting the two-photon interference with such a function (Eq. (1)), we get a visibility of $V = 46\%$. This relatively low visibility is due to the high number of accidental coincidences. The latter are themselves due to simultaneous (i.e., within the 400-psec coincidence window) dark counts in both detectors or to one photon of a pair detected simultaneously with a dark count of the other detector, while the other photon was absorbed by the fiber. A quantitative evaluation of these effects is difficult because of the dead time (≈ 4 μsec) of the TPHC and of afterpulses. The total accidental counts were measured by introducing an additional delay line, thus placing the coincidence peaks apart from the discriminator window. We obtained an average of 150 coincidences per 20 sec [25]. Subtracting these, the obtained visibility is $(81.6 \pm 1.1)\%$ [26]. This is the visibility one would expect for noiseless detectors.

Since we found the same visibility in a ''short-distance'' Bell experiment in our laboratory, we assume that the devia-

tion from the maximum theoretical value of 1 is not due to the physical distance between the interferometers. The missing 18% has to be traced back to the imperfect performance of our devices. Remaining birefringence and chromatic dispersion effects in the interferometers, unequal transmission probabilities for the different arms, and imperfect suppression of the unwanted satellite coincidence peaks are possible explanations. However, the main reduction can probably be found in small wavelength fluctuations of the pump laser.

As mentioned in the introduction, this experiment was not primarily designed to test local hidden variables. However, it is interesting to evaluate by how much the Bell inequality could be violated in such a long-distance Bell experiment. This inequality provides also a natural criterion for a ''strong quantum correlation'': The correlation is strong if the two-photon interference visibility is larger than the 71% necessary to infer a violation of Bell's inequality. It is remarkable that this definition of ''strong quantum correlation'' corresponds also precisely to the visibility necessary in quantum cryptography to guarantee the security of the quantum communication channel: If the perturbations introduced by Eve while trying to eavesdrop are weak, in the precise sense that the two-photon visibility remains larger than 71%, then one can prove that her optimal information on Alice data is necessarily lower than Bob's information [27]. Conversely, if the perturbations are strong, i.e., if the two-photon visibility reduced below 71%, then Eve's information may be larger than Bob's one. Looking at the obtained visibility after subtraction of the accidental counts of $(81.6 \pm 1.1)\% > 1/\sqrt{2} \approx 0.71$, we can infer a violation of the Bell inequality by ten standard deviations [28].

In conclusion, this experiment gives evidence that the spooky action between entangled photons does not break down when separating the particles by a physical distance of 10 km. However, we acknowledge that neither this nor any of the previous experiments can close the detection loophole [29]. Hence, in order to deduce nonlocality from existing data, additional assumptions are needed. In particular, and most importantly in our opinion, one has to assume that the detected pairs of particles form a fair sample of the set of all emitted pairs. Further investigations with interferometers and a pump laser of better performance should be made, also varying the fiber lengths. In a next experiment we plan to test Bell's inequalities with truly random settings of the analyzers in order to rule out every subluminal communication between the different experimental parts, thus obeying Einstein locality. In addition to tests of fundamental physics, the possibility of creating entangled photons at a telecommunications wavelength and the fact that the different experimental parts (especially the source) are of small dimensions and easy to handle opens the field for future application of photon pairs. More generally, it nicely illustrates a general aim of the field of quantum information processing: It turns quantum conundrums into potentially useful processes.

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[26] To determine the visibility corresponding to the measured data, we apply a least-squares fit (χ^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 χ^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.

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