Violation of Bell Inequalities by Photons More Than 10 km Apart

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A Franson-type test of Bell inequalities by photons 10.9 km apart is presented. Energy-time entangled photon pairs are measured using two-channel analyzers, leading to a violation of the inequalities by 16 standard deviations without subtracting accidental coincidences. Subtracting them, a two-photon interference visibility of 95.5% is observed, demonstrating that distances up to 10 km have no significant effect on entanglement. This sets quantum cryptography with photon pairs as a practical competitor to the schemes based on weak pulses. [S0031-9007(98)07478-X]

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Quantum theory is nonlocal. Indeed, quantum theory predicts correlations among distant measurement outcomes that cannot be explained by any theory which involves only local variables. This was anticipated by Einstein, Podolsky, and Rosen [1] and by Schrödinger [2], among others, and first demonstrated by Bell in 1964 with his now famous inequality [3]. However, the nonlocal feature cannot be exploited for superluminal communication [4]. Hence, there is no contradiction with relativity, though there is clearly a tension. Physicists disagree about the significance and importance of this tension. This led Shimony to name this situation "peaceful coexistence between quantum mechanics and relativity" [5].

Why should one still bother about quantum nonlocality despite the fact that all experiments so far are in agreement with quantum theory [6–9]? The traditional motivations are based on fundamental questions on the meaning and compatibility of our basic theories, quantum mechanics, and relativity: to date, no experiment to test Bell's inequality has been loophole-free [10–12] and no experiment so far has tested relativistic nonlocality (also named multisimultaneity [13]). Recently, additional motivations to investigate quantum nonlocality arose based on the potential applications of the fascinating field of quantum information processing: all of the quantum computation and communication is based on the assumption that quantum systems can be entangled and that the entanglement can be maintained over long times and distances [14].

In 1997 we have demonstrated that two-photon correlations remain strong enough over 10 km so that a violation of Bell inequalities could be expected [15]. In this Letter we report on a new experiment using two-channel analyzers in which all four coincidence rates have been measured simultaneously. This arrangement, realized for the first time by Aspect *et al.* in 1982 [7], allows one to directly obtain the correlation coefficient that defines the Bell inequalities. Our experiment demonstrates a violation of Bell inequalities with photons more than 10 km apart without subtracting the accidental coincidences [16]. In addition, an experiment with three interferometers, two on one end and the third at the other end (10 km away), is presented. The two nearby interferometers analyze the incoming photons randomly, the choice being made by a passive beam splitter. This setup enables one to test directly the Clauser-Horne-Shimony-Holt (CHSH) form of Bell inequalities [17]. Our experiment establishes also the feasibility of quantum cryptography with photon pairs [18] (in opposition to weak coherence pulses) over a significant distance.

For our Franson-type test of Bell inequalities [19], we produce energy-time entangled photons by parametric down-conversion (Fig. 1). Light from a semiconductor laser with an external cavity (10 mW at 655 nm, $\Delta\nu <$ 10 MHz) passes through a dispersion prism P to separate out the residual infrared fluorescent 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 [20]. Behind the crystal, the pump light 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. Using a telecommunications

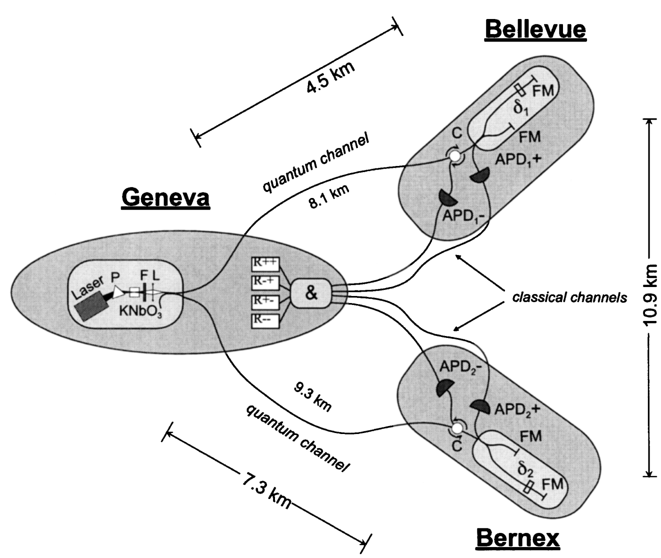

FIG. 1. Setup for experiment 1. See text for detailed description.

fiber network, the photons are then analyzed by all-fiber interferometers located 10.9 km apart from one another in the small villages of Bellevue and Bernex, respectively. The source, located in Geneva, was 4.5 km away from the first analyzer and 7.3 km from the second, with connecting fibers of 8.1 and 9.3 km length, respectively, as indicated in Fig. 1. Our interferometers use both the Michelson configuration and have a long and a short arm. In order to compensate all birefringence effects in the arms (i.e., to stabilize the polarization), we employ so-called Faraday mirrors (FM) to reflect the light [21]. At the input ports, we use optical circulators (C). These devices guide the light from the source to the interferometer, but, thanks to the nonreciprocal nature of the Faraday effect, they guide the light reflected back from the interferometer to another fiber, serving as a second output port. The output ports of each interferometer are connected to photon counters [22]. We label the "direct" port as "+," the one connected to the circulator "−." To control and change the phases (δ_1, δ_2), the temperature of the interferometers can be maintained constant or can be slowly varied.

Since the arm length difference is 5 orders of magnitude larger than the single photon coherence length, there is no single photon interference. However, the path-length difference in both interferometers is precisely the same, with a subwavelengths accuracy. Moreover, this imbalance is 2 orders of magnitude smaller than the coherence length of the pump laser. Hence, an entangled state can be produced where either both photons pass through the short arms or both use the long arms. Noninterfering possibilities (the photons pass through different arms) can be discarded using a high resolution coincidence technique [23].

To ensure symmetry for the two channels of each analyzer, we adjusted the count rates of the detectors attached to the same interferometer. Typical rates are 39.5 kHz including 26 kHz dark count rates. The classical signals from the photon detectors are transmitted back to Geneva. We measure the four different numbers of time-correlated events $R_{i,j}(\delta_1, \delta_2), (i, j = \pm)$, where, i.e., R_{+-} denotes the coincidence count rate between the + labeled detector at apparatus 1 and the − labeled one at apparatus 2. (For more technical information see our full length paper [24].) The correlation coefficient now reads [7]

$$E(\delta_1, \delta_2) := \frac{R_{++}(\delta_1, \delta_2) - R_{+-}(\delta_1, \delta_2) - R_{-+}(\delta_1, \delta_2) + R_{--}(\delta_1, \delta_2)}{R_{++}(\delta_1, \delta_2) + R_{+-}(\delta_1, \delta_2) + R_{-+}(\delta_1, \delta_2) + R_{--}(\delta_1, \delta_2)} \tag{1}$$

and permits one to determine the Bell parameter

$$S = |E(d_1, d_2) + E(d_1, d_2') + E(d_1', d_2) - E(d_1', d_2')| \leq 2, \tag{2}$$

where d_i, d_i' $(i = 1, 2)$ denote values of phases δ_i. The above inequality, known as Bell-CHSH inequality [17], is satisfied by all local theories. Quantum mechanics predicts a maximal value for the Bell parameter $S = 2\sqrt{2}$.

Another type of Bell inequality was given by Clauser and Horne [25] for an experiment with polarizers. A similar argument can be applied to experiments using interferometers: if it is found experimentally that the single count rates are constant, and that $E(\delta_1, \delta_2) = E(\Delta)$ holds where $\Delta = (\delta_1 + \delta_2)$ is the sum of the phases in both interferometers, then Eq. (2) reduces to $S = |3E(\Delta) - E(3\Delta)| \leq 2$. Beyond that, if it is found that the correlation coefficient E is described by a sinusoidal function of the form $E = V \cos(\Delta)$ with visibility V, then the Bell parameter S becomes $S = V 2\sqrt{2}$. Hence, observing a visibility V greater than $V \geq 1/\sqrt{2} \approx 0.707$ will in this case directly show that description of nature as provided by quantum mechanics is unreconcilable with the assumptions leading to the Bell inequalities.

In a first experiment, we changed the path length differences of both interferometers simultaneously, but at different speeds, and recorded the coincidence count rates as a function of time, hence of phases δ_1, δ_2. Typical mean coincidence count rates are about 130 in 20 sec. From the four rates, we calculate the correlation coefficient $E(\delta_1, \delta_2)$ [Eq. (1)]. Comparing the correlation functions when both interferometers scan in the same direction, when both scan in opposite directions, and when only one is scanning, we can confirm that in a Franson-type interferometer the fringes can be described by a sinusoidal function and depend on the sum of the two phases $(\delta_1 + \delta_2)$. In addition, no phase dependent variation of the single count rates could be observed. Hence we can calculate the parameter S from the observed visibilities. In all cases we find values exceeding the limit given by the Bell inequalities by at least 9 standard deviations (σ). The raw data for one of the best violations yield $S_{\text{raw}} = (0.853 \pm 0.009) 2\sqrt{2}$, corresponding to a violation by 16σ. Most of the difference between this result and the theoretical prediction can be attributed to accidental coincidences [26]. Indeed, from the measured single count rates (39.5 kHz) and the coincidence window of 550 ± 10 ps one can estimate the accidental coincidence rate to be 25.7 ± 0.5 per 30 sec (assuming that all events at both detectors are uncorrelated). This rate is in excellent agreement with the one we measured, placing the coincidence window apart from the coincidence peak (26.4 ± 1.3 per 30 sec). Subtracting the accidental coincidences, we obtain $S_{\text{net}} = (0.955 \pm 0.01) 2\sqrt{2}$, corresponding to a violation of the inequality by 24.8σ. Since the visibility of the correlation function after subtracting the accidentals is close to 1, one has to conclude that the distance does not affect the nonlocal aspect of quantum mechanics, at least for distances up to 10 km [27].

In a second experiment, we replaced one of the interferometers by two interferometers connected to the fiber from the source by a fiber coupler (i.e., a beam splitter). These two interferometers, however, used no circulators; hence only one detector per interferometer could be used. For this reason we can measure only two of the four coincidence count rates needed to calculate the correlation function [Eq. (1)]. To infer from the measured functions to the correlation function we thus have to assume the same symmetry between the coincidence functions as we found in the experiment described before. With this quite natural assumption, we can evaluate the correlation coefficients $E(d_1, d_2)$ and $E'(d_1', d_2)$ at the same time, hence for exactly the same setting δ_2. Figure 2 shows the correlation coefficients observed when changing the phase δ_2 in the Bernex interferometer. We find again sinusoidal functions. Visibilities are about 78% without and about 96% with subtraction of accidental coincidences. (The smaller raw visibility compared to the first experiment is due to 50% additional losses of true coincidences in the coupler while the accidental ones stay almost constant.) We can now directly evaluate the value of the Bell parameter S [Eq. (2)] from the correlation coefficients for two different values d_2, d_2'. For the indicated points we find $S_{\text{raw}} = 2.38 \pm 0.16$ and $S_{\text{net}} = 2.92 \pm 0.18$ leading to violations of 2.4 and 5.1 standard deviations, respectively, and confirming once again the quantum mechanical predictions.

Assuming that the passive coupler randomly selects which interferometer analyzes the photon, this experiment can be considered as involving truly random choices for the analyzer settings, similar to the Aspect experiment with time varying analyzers [8], and as required to close the locality loophole [11], at least on one side of the experiment. Since we find the same net visibility as in the first experiment, we can infer that the random choice at the beam splitter does not change the result of the measurement. One could argue that the choice is not really random, since the assumed local hidden variable could determine into which interferometer the photon is

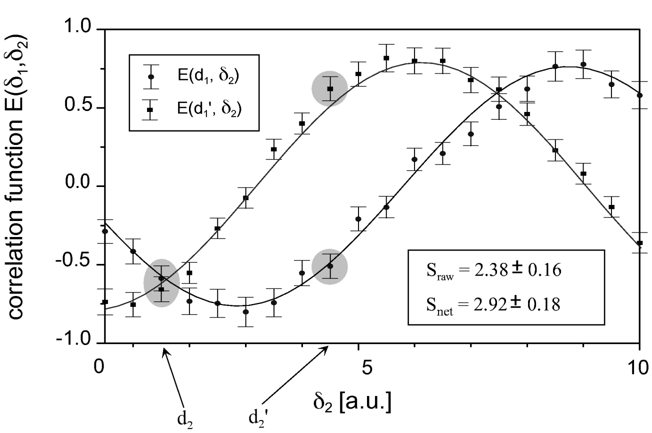

FIG. 2. Result for experiment 2: The correlation functions $E(d_1, \delta_2)$ and $E(d_1', \delta_2)$ are plotted as a function of phase δ_2. From the four indicated points one obtains $S_{\text{raw}} = 2.38 \pm 0.16$ and $S_{\text{net}} = 2.92 \pm 0.18$, leading to a violation of the CHSH-Bell inequality of 2.4 and 5.1 standard deviations, respectively.

guided. Note first, however, that it is difficult to think of a better random number generator than a quantum one (based, e.g., on a beam splitter as in our case), and next that if the hidden variable could determine a preferred interferometer, it could determine equally well whether the photon is detected at all or remains undetected. This is the basis of the detection loophole, an interesting possibility still open for local theories [10].

Another way to look at our experiments is quantum cryptography based on entangled particles [18]. The quantum bit error rate (QBER) [28] of this scheme is related to the visibility V before removal of the accidental coincidences: QBER $= \frac{1-V}{2}$. Note that subtracting the accidentals is impossible for quantum cryptography, as there is no way to determine which coincidence counts are accidental and which are due to a photon pair. From our measured raw visibility of 85.2% we infer a QBER of 7.4%. This is higher than the QBER obtained in experiments using weak pulses [14]. Nevertheless, our result demonstrates that it is promising for practical implementation, not so far from the schemes working with weak pulses. A fast switching in order to really exchange a key still has to be implemented. This switching can be done either by a phase modulator or, as we did in our last experiment, by using a fiber coupler connected to two interferometers with appropriate phase differences. The advantage of the latter setup is that no fast random generator and electronic switching is necessary. However, since the QBER increases with increasing losses, this setup would in our case be limited to around 10 km, a distance which is determined by the number of created photon pairs, overall losses, and detector performance. A better way to do entanglement-based quantum cryptography would be to use a source employing nondegenerate phase matching in order to create correlated photons of different wavelengths, one at 1310 nm and the other one around 900 nm. This would allow one to use more efficient and less noisy silicon photon counting modules to detect the photons of the lower wavelength. To avoid the high transmission losses of photons of this wavelength in optical fibers, the interferometer(s) measuring these photons could be placed next to the source. First investigations show that quantum cryptography over tens of kilometers should be possible. It is interesting to note that besides ensuring the security of entanglement-based quantum cryptography, the Bell inequality is even connected to the one qubit application of quantum cryptography: a quantum channel can be used safely if and only if the noise in the channel is small enough to allow a violation of Bell inequality [29].

As already mentioned in the introduction, no experiment up to date has been loophole-free. Assuming that our results are not affected by the presence of these loopholes, this experiment demonstrates that energy-time entanglement is robust enough to manifest itself in the violation of Bell inequalities by photons more than 10 km apart. It also opens the door to several new possibilities: close the locality loophole, dense coding [30], entanglement swapping [31], and quantum teleportation [32] at large distances as well as for entanglement-based quantum cryptography. There is also another interesting proposal: set the two analyzer in motion such that each analyzer in its own inertial frame measures the photon pairs first [13].

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[27] Besides determining the correlation functions, we made fits of the underlying coincidence functions $R_{i,j}$ $(i, j = \pm 1)$, as well [24]. We find them to be in close agreement with the values for the correlation function. However, even if the single count rates show almost perfect symmetry, we find a difference in the mean values of the coincidence counts. Therefore the sum of the coincidence rates of one detector with both detectors on the other side (i.e., $R_{++} + R_{+-}$) is not constant. The origin of this difference is due to different spectral quantum efficiencies of different detectors in connection with the large bandwidth of the down-converted photons. However, if summing over all coincidence rates, we always find the same value, confirming that the size of the detected sample of photon pairs is constant.

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