RAPID COMMUNICATIONS

The Rapid Communications section is intended for the accelerated publication of important new results. Since manuscripts submitted to this section are given priority treatment both in the editorial office and in production, authors should explain in their submittal letter why the work justifies this special handling. A Rapid Communication should be no longer than 4 printed pages and must be accompanied by an abstract. Page proofs are sent to authors.

Postselection-free energy-time entanglement

D. V. Strekalov, T. B. Pittman, A. V. Sergienko, and Y. H. Shih

Physics Department, University of Maryland Baltimore County, Baltimore, Maryland 21228

P. G. Kwiat

Physics Division, P-23, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

We report a two-photon interference experiment that realizes a postselection-free test of Bell's inequality based on energy-time entanglement. In contrast with all previous experiments of this type, the employed entangled states are obtained *without* the use of a beam splitter or a short coincidence window to "throw away" unwanted amplitudes. A $(95.0 \pm 1.4)\%$ interference fringe visibility is observed, implying a strong violation of the Bell inequality. The scheme is very compact and has demonstrated excellent stability, suggesting that it may be useful, for example, in practical quantum cryptography. [S1050-2947(96)50607-4]

Two-photon entanglement has received a great deal of attention recently due to its role in fundamental problems of quantum theory, such as tests of Bell's inequalities and the Einstein-Podolsky-Rosen "paradox" [1–4], and also due to its potential practical applications in, for example, quantum cryptography [5,6] and quantum computing [7]. The classic example of a two-particle entangled state was suggested by Einstein, Podolsky, and Rosen (EPR) in their famous *gedankenexperiment* [8]:

$$|\Psi\rangle = \int da \int db \ \delta(a+b-c_0)|a\rangle|b\rangle, \qquad (1)$$

where a and b may be, for example, the momentum of the spatially separated particles, and c_0 is a constant. State (1) is entangled because it cannot be written as a product of single-particle states. Remarkably, although the values of a and b are not defined, the measurement of one of them (e.g., a) determines the value of the other one with certainty $(b = c_0 - a)$.

The most convenient source of entangled photon pairs is spontaneous parametric down-conversion (SPDC), the nonlinear optical process in which a pump photon is converted into a pair of photons, called *signal* and *idler* [3]. According to the theory of SPDC [9,10], the state of the emitted pair is energy-entangled [cf. (1)]:

$$|\Psi\rangle = \int d\omega \int d\omega' \ \delta(\omega + \omega' - \omega_p)|\omega\rangle_s|\omega'\rangle_i, \qquad (2)$$

where we imply that pinholes select one signal and one (matched) idler mode, thus eliminating integration over angular variables.

Following the pioneering work of Franson [11], a series of down-conversion experiments were based on states entangled with respect to *energy-time* variables [12–14]. Each of the down-conversion photons is directed into an unbalanced Mach-Zehnder interferometer (Fig. 1, with nonpolarizing beam splitters) with a long (L) and a short (S) path. Since the path difference in each interferometer is much greater than the coherence length of the signal and idler, no interference is seen in a single-detector counting rate. Nevertheless, interference is observable in the rate of coincidences. The original states constituted a product $(L_1 + S_1)(L_2 + S_2)$ whose noninterfering, yet coincidence-giving terms $L_1 S_2$ and $S_1 L_2$ had to be discarded in order to emulate an entangled state. To achieve this, the coincidence circuit had an acceptance window shorter than the light trav-
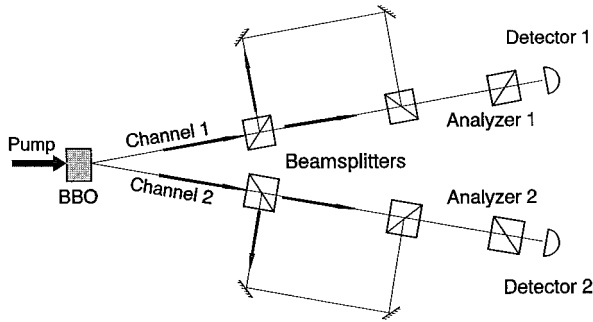
FIG. 1. With nonpolarizing beam splitters, this is a simplified scheme of Franson's proposal [11]. When polarizing beam splitters are substituted, and polarization-entangled photons are used, a postselection-free implementation may be realized: in channel 1, the horizontally polarized photon *always* goes the long way, and the vertically polarized one, the short way; in channel 2, the opposite happens. After the analyzers 1 and 2 the two terms of the state become indistinguishable with regard to polarization, and coincidences between detectors 1 and 2 reveal the nonlocal interference as any of the path lengths is changed.

eling time difference between the long and short arms, thus realizing a detection postselection. Interference of the two remaining indistinguishable amplitudes L_1L_2 and S_1S_2 displayed high visibility fringes and led to a violation of Bell's inequality [13]. If all four terms are kept, the interference still persists, but with the visibility limited to 50% [12]. This makes it unsuitable for the EPR argument because now a measurement of one particle's energy would not give a *certain* value for the other particle's energy; it is consequently inadequate for a definitive Bell's inequality test, which requires visibility greater than $1/\sqrt{2} \approx 71\%$ (see, e.g., Ref. [4]).

Note that the detection postselection is a *classical* selection process, and not a quantum-mechanical projection [15]. However, the experiments relying on it are still valid for testing Bell-type inequalities if an additional assumption is made that the photons in the subensemble of discarded events are not any different from those we choose to look at. This is much stronger than the usual *fair sampling* assumption accounting for nonperfect detectors, and it has been criticized for opening a loophole in Bell inequalities' violation [16]. It is therefore important to perform Bell-type experiments with genuine entangled states, without discarding any counts. As we discuss below, such an experiment can also have important ramifications for quantum cryptography.

Recently, a postselection-free *polarization* entangled state was demonstrated using type-II SPDC [17]: $|\Psi\rangle \sim |h\rangle_1|v\rangle_2 + |v\rangle_1|h\rangle_2$, where h and v stand for a horizontally (ordinary) and vertically (extraordinary) polarized photon, respectively. This state was used for preparation of different Bell states [18], all displaying very convincing violations of Bell's inequality. In the present paper we use the same source to enable a postselection-free implementation of the Franson experiment [19] involving *energy-time* entanglement. The basic idea of our experiment can be seen with the help of Fig. 1, now with polarizing beam splitters. There are now only two different ways to get a coincident detection: ether the horizontally polarized photon in channel 1 passes through the long path, while its vertically polarized twin
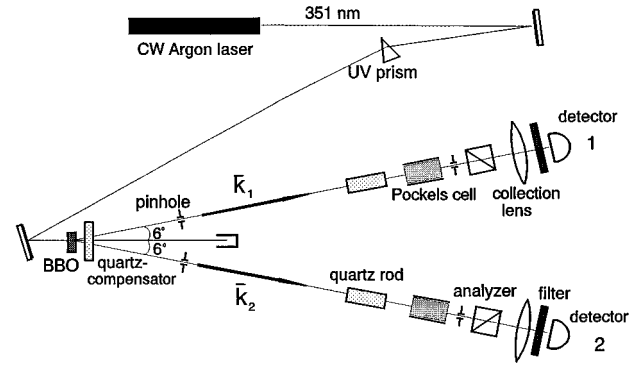

FIG. 2. Experimental setup. The dashed line represents the UV laser beam that pumps the crystal (BBO). The signal and idler beams (solid lines) propagate at 6° relative to the pump in the same plane. Each of them passes through a quartz compensator, quartz rod, Pockels cell, and analyzer. Then both beams are focused by lenses to the detectors marked 1 and 2, passing through similar interference filters.

brother passes through the long path in channel 2; or both photons take the short paths. This situation is essentially different from previous versions of Franson's proposal [11–13], because the unwanted long-short and short-long amplitudes *simply do not exist.*

The scheme of our actual experiment is shown in Fig. 2. The single-mode UV (351-nm) beam from a cw argon laser passes through a fused silica prism to separate out the plasma luminescence and then pumps the nonlinear crystal (BBO). The 3-mm-thick BBO crystal is cut for type-II SPDC, so that the angle between the optical axis and the pump $\theta \approx 49°$ allows collinear phase matching for degenerate frequency (702-nm) photons. Tilting the crystal (and so changing θ by several degrees) we produce polarization-entangled degenerate signal and idler photons of a given pair exiting the crystal at equal, yet opposite, coplanar angles of 6° with respect to the pump [20].

The interferometers in Fig. 1 are implemented by quartz rods (2 cm long) placed in channels 1 and 2. But in contrast with Fig. 1, the birefringent rods delay the slow polarization component relative to the fast one due to their different refraction indexes. This delay corresponds to $\Delta L = \Delta n_{\text{quartz}} L \approx 180$ μm, which is greater than the down-conversion photons' coherence length (160 μm), basically determined by the spectral bandwidth of the interference filters ($\Delta \lambda = 3$ nm). Therefore, only minimal first-order interference effects are observable.

The quartz rods are followed by Pockels cells whose orientations are locked to those of rods. They may be simply considered as adjustable ''fine-tuning'' extensions of the rods, adding a delay on the scale of fractions of a wavelength. Polarization analyzers (Glan-Thompson prisms) are installed in each channel after the Pockels cells. The signals from the detectors (dry ice cooled avalanche photodiodes operating in Geiger mode) are sent to counters and a coincidence circuit with a 10-ns acceptance window.

The fast axes of both rods are oriented at angles φ_1 and φ_2 relative to the vertical direction, so that the polarization components of $|\Psi\rangle$ are projected: $|h\rangle_i = |s\rangle_i \sin \varphi_i + |f\rangle_i \cos \varphi_i$, $|v\rangle_i = |s\rangle_i \cos \varphi_i - |f\rangle_i \sin \varphi_i$, $i = 1,2$, where s and f are the
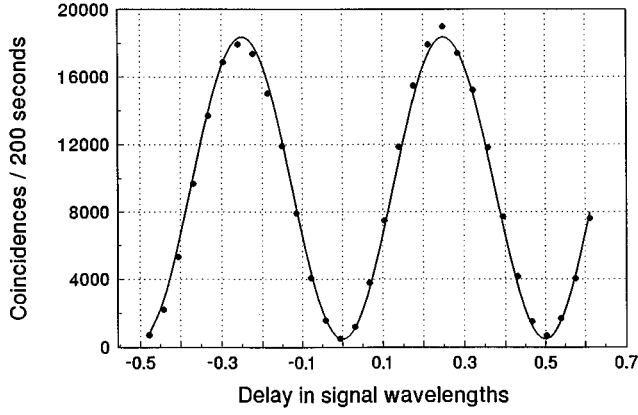
FIG. 3. Experimental data and best fit. The number of coincident counts per 200 s is shown vs the delay of the slow component (relative to the fast one) by *each* of the two Pockels cells. The delay is proportional to voltage applied to the cell. The visibility of the fringes is (95.0±1.4)%. The error bars are represented by the size of the point.

slow and fast polarization components. The state $|\Psi\rangle$ then becomes

$$|\Phi\rangle \sim (|s\rangle_1|s\rangle_2 e^{i(\alpha+\beta)} - |f\rangle_1|f\rangle_2)\sin(\varphi_1+\varphi_2)$$
$$+ (|s\rangle_1|f\rangle_2 e^{i\alpha} - |f\rangle_1|s\rangle_2 e^{i\beta})\cos(\varphi_1+\varphi_2), \quad (3)$$

where α and β are the phase shifts introduced by each of the Pockels cells [21]. The first term of (3) corresponds to the $L_1L_2 + S_1S_2$ term of Franson's scheme, while the last one corresponds to the $S_1L_2 + L_1S_2$ term, providing a variable fraction of noninterfering background, which vanishes when the rods are oriented so that $\cos(\varphi_1+\varphi_2)=0$. Furthermore, if both analyzers are set at 45° relative to the fast and slow axes of the rods (i.e., at $\varphi_i + 45°$ from vertical direction), then remaining terms of (3) become indistinguishable with regard to polarization [22] and the coincidence rate will be proportional to $1 - \cos(\alpha+\beta)$. Note that it has in principle 100% visibility fringes that depend only on the *sum* of the separated phases. This is a manifestation of the nonlocality implicit in the states (2) and (3).

We have experimentally verified (3) for two sets of φ_i: $\varphi_1 = \varphi_2 = 45°$ and $\varphi_1 = 0°$, $\varphi_2 = 90°$. Typical results are shown in Fig. 3. For these data we varied α and β together, keeping $\alpha = \beta$. Therefore the period of modulations is only half of the signal (and idler) wavelength, i.e., it is equal to the pump wavelength. Fitting the experimental data by a sinusoidal curve, we find a visibility (95±1.4)% which exceeds the limit of 71% by approximately 17 standard deviations. Therefore, we can infer a strong violation of Bell's inequality, modulo the usual fair sampling assumption.

Aside from the higher quality interference, our scheme has several major advantages over the earlier realizations. First, because our experiment does not involve any time discrimination, the only criterion specifying the upper limit of the coincidence circuit window size is that there be only one photon pair in the system at a time. Thus one could employ much slower detectors and a much larger coincidence window and still observe high-visibility fringes.

By spatially overlapping "long" and "short" paths in the quartz polarization interferometers, we have further increased their stability. The stability is basically determined by the birefringent properties of the quartz rods and the Pockels cells, and these are very stable with respect to time and temperature variations. To verify this, we scanned our interferometer over one wavelength range four times with 8-hour intervals between the first and last scans, and found a phase drift of only ~1°, and no statistically significant change in the visibility (~97%). No environmental thermostabilization was used, other than a counterproductive university laboratory air conditioner.

These encouraging results indicate that the scheme may be successfully employed in applications requiring strong nonlocal correlations, a compact system, and phase stability over long periods of time. In particular, it could be used for a two-photon version of quantum cryptography (see, for example, Ref. [6]). In this type of cryptographic protocol, a sender and a receiver share a secret "key," randomly choosing the phases of their interferometers, and using public communication to keep only the results for those cases where the phase sum should grant perfect correlation, i.e., $\alpha + \beta = n(\pi/2)$. One major source of errors then is their failure to keep the sum of phases of both interferometers constant due to their drift. Maintaining two separated interferometers stable over a long period of time is nontrivial, especially if they require large path-length imbalances to eliminate the noninterfering "long-short" background, as has been the case with several reported dual-interferometer cryptographic systems [23]. In addition to the simple fact that 50% of the photons must be discarded outright (while in our scheme *the other outputs* of the analyzers can be used simultaneously, since they will display similar high-visibility correlation fringes), the need for timing postselection in these arrangements requires either very good time resolution of the *record* of detections, to allow subsequent removal of the "long-short" events, or transferring the actual detection signal from the sender to the receiver, to allow an electronic coincidence circuit to make the discrimination. The former is very difficult (the timing information of every detection would need to be recorded to within nanoseconds), while the latter demands nanosecond resolution of the "public channel."

An attempt to soften the time resolution demand by using interferometers with longer bases will lead to loss of stability. Our present scheme overcomes these problems by making the discrimination condition irrelevant, in addition to keeping the phases much more stable [6,24].

Summarizing the performed experiment: First, the violation of Bell's inequality based on *energy-time variables without throwing away terms of the state* is of interest in the argument between quantum mechanics and a local hidden-variable approach. Second, the polarization interferometer employed in our experiment has proven to be a stable and very convenient device, possibly helpful in two-photon quantum cryptography and other two-photon interference applications.

[1] J. S. Bell, Physics **1**, 195 (1964).

[2] Two-photon states have been produced via atomic cascade decay, for example, in S. J. Freedman and J. F. Clauser, Phys. Rev. Lett. **28**, 938 (1972); J. F. Clauser, *ibid.* **36**, 1223 (1976); A. Aspect, J. Dalibard, and G. Roger, *ibid.* **49**, 1804 (1982).

[3] Parametric down-conversion is used, for example, in Y. H. Shih and C. O. Alley, Phys. Rev. Lett. **61**, 2921 (1988); Z. Y. Ou and L. Mandel, *ibid.* **61**, 50 (1988).

[4] J. G. Rarity and P. R. Tapster, Phys. Rev. Lett. **64**, 2495 (1991).

[5] A. K. Ekert, Phys. Rev. Lett. **67**, 661 (1990).

[6] A. K. Ekert, J. G. Rarity, P. R. Tapster, and G. M. Palma, Phys. Rev. Lett. **69**, 1293 (1992); J. G. Rarity, P. C. M. Owens, and P. R. Tapster, J. Mod. Opt. **41**, 2435 (1994).

[7] A. Barenco, D. Deutsch, A. Ekert, and R. Jozsa, Phys. Rev. Lett. **74**, 4083 (1995); T. Sleator and H. Weinfurter, *ibid.* **74**, 4807 (1995); J. I. Cirac and P. Zoller, *ibid.* **74**, 4091 (1995).

[8] A. Einstein, B. Podolsky, and N. Rosen, Phys. Rev. **47**, 777 (1935).

[9] D. N. Klyshko, *Photons and Nonlinear Optics* (Gordon and Breach, New York, 1988).

[10] M. H. Rubin, D. N. Klyshko, Y. H. Shih, and A. V. Sergienko, Phys. Rev. A **50**, 5122 (1994).

[11] J. D. Franson, Phys. Rev. Lett. **62**, 2205 (1989).

[12] Z. Y. Ou, X. Y. Zou, L. J. Wang, and L. Mandel, Phys. Rev. Lett. **65**, 321 (1990); J. G. Rarity *et al.*, *ibid.* **65**, 1348 (1990); J. D. Franson, Phys. Rev. A **44**, 4552 (1991).

[13] J. Brendel, E. Mohler, and W. Martienssen, Europhys. Lett. **20**, 575 (1992); P. G. Kwiat, A. E. Steinberg, and R. Y. Chiao, Phys. Rev. A **47**, R2472 (1993); P. R. Tapster, J. G. Rarity, and P. C. M. Owens, Phys. Rev. Lett. **73**, 1923 (1994); R. Y. Chiao, P. G. Kwiat, and A. E. Steinberg, Quantum Semiclass. Opt. **7**, 259 (1995).

[14] Another type of Bell-inequality experiment involving entanglement in *momentum* [M. A. Horne, A. Shimony, and A. Zeilinger, Phys. Rev. Lett. **62**, 2209 (1989)] was performed by Rarity and Tapster [4]. This experiment relied on multiple transverse modes, thus realizing a postselection-free entanglement in *momentum-space* variables, in contrast with the experiments discussed here requiring multiple longitudinal modes but a single transverse one.

[15] Indeed, following the commonly used Glauber theory [R. J. Glauber, Phys. Rev. **130**, 2529 (1963); **131**, 2766 (1963)], for average coincidence counting rate:

$$R_c = \frac{1}{T}\int_0^T \int_0^T dt' \, dt \, S(t-t',\tau)\langle\Psi|\mathbf{E}_1^{(-)}\mathbf{E}_2^{(-)}\mathbf{E}_1^{(+)}\mathbf{E}_2^{(+)}|\Psi\rangle,$$

where **E** are electrical fields at detectors 1 and 2, we see that the postselection process is described by a time-averaging with the window function $S(t_1-t_2,\tau)$, which basically tells us how the coincidence circuit works, rather than by $\langle\Psi|\mathbf{E}_1^{(-)}\mathbf{E}_2^{(-)}\mathbf{E}_1^{(+)}\mathbf{E}_2^{(+)}|\Psi\rangle$, whose evaluation completes the quantum-mechanical part.

[16] E. Santos, Phys. Rev. Lett. **66**, 1388 (1991); L. De Caro and A. Garuccio, Phys. Rev. A **50**, R2803 (1994).

[17] P. G. Kwiat *et al.*, Phys. Rev. Lett. **75**, 4337 (1995).

[18] S. L. Braunstein, A. Mann, and M. Revzen, Phys. Rev. Lett. **68**, 3259 (1992).

[19] M. Zukowski and J. Pykacs, Phys. Lett. A **127**, 1 (1988); P. G. Kwiat, Phys. Rev. A **52**, 3380 (1995).

[20] An extra birefringent crystal is needed which introduces *one half* of the BBO's relative optical delay to compensate for a longitudinal walk-off inside the BBO [10]. We use a 12.8-mm rod of crystal quartz for this purpose.

[21] We omit the constant phase shift due to the quartz rods. Technically, this shift is compensated by applying an offset voltage to one of the Pockels cells.

[22] Up to this point the state was entangled *both* in energy *and* in polarization. Such double entanglement is studied by T. B. Pittman, Y. H. Shih, A. V. Sergienko, and M. H. Rubin, Phys. Rev. A **51**, 3495 (1995).

[23] P. D. Townsend, J. G. Rarity, and P. R. Tapster, Electron. Lett. **29**, 634 (1993). Only a single photon passes through two interferometers in this protocol, but the timing and stability issues remain. Note, however, that a polarization-division scheme similar to ours was incorporated into a *single photon* protocol by C. Marand and P. D. Townsend, Opt. Lett. **20**, 1695 (1995).

[24] The problem of preserving the polarization state purity while the photons are transmitted over a large distance may be reduced by using polarization-preserving fibers, cut in half and orthogonally coupled so that they compensate the longitudinal walk-off due to their birefringence. In principle, extra stability may be gained using the feedback technique already demonstrated for a one-photon polarization setup by J. D. Franson and H. Ilves, J. Mod. Opt. **41**, 12 (1994); **41**, 2391 (1994). In this way one could compensate for relative environmental variations experienced by the two halves of the fiber.