Experimental Realization of Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*: A New Violation of Bell's Inequalities

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The linear-polarization correlation of pairs of photons emitted in a radiative cascade of calcium has been measured. The new experimental scheme, using two-channel polarizers (i.e., optical analogs of Stern-Gerlach filters), is a straightforward transposition of Einstein-Podolsky-Rosen-Bohm *gedankenexperiment*. The present results, in excellent agreement with the quantum mechanical predictions, lead to the greatest violation of generalized Bell's inequalities ever achieved.

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In the well-known Einstein-Podolsky-Rosen-Bohm *gedankenexperiment*[1] (Fig. 1), a source emits pairs of spin-$\frac{1}{2}$ particles, in a singlet state (or pairs of photons in a similar nonfactorizing state). After the particles have separated, one performs correlated measurements of their spin components along arbitrary directions $\vec{a}$ and $\vec{b}$. Each measurement can yield two results, denoted ±1; for photons, a measurement along $\vec{a}$ yields the result +1 if the polarization is found parallel to $\vec{a}$, and −1 if the polarization is found perpendicular. For a singlet state, quantum mechanics predicts some correlation between such measurements on the two particles. Let us denote by $P_{\pm\pm}(\vec{a},\vec{b})$ the probabilities of obtaining the result ±1 along $\vec{a}$ (particle 1) and ±1 along $\vec{b}$ (particle 2). The quantity

$$E(\vec{a},\vec{b}) = P_{++}(\vec{a},\vec{b}) + P_{--}(\vec{a},\vec{b}) - P_{+-}(\vec{a},\vec{b}) - P_{-+}(\vec{a},\vec{b}) \tag{1}$$

is the correlation coefficient of the measurements on the two particles. Bell[2] considered theories explaining such correlations as due to common properties of both particles of the same pair; adding a locality assumption, he showed that they are constrained by certain inequalities that are not always obeyed by the predictions of quantum mechanics. Such theories are called[3] "realistic local theories" and they lead to the generalized Bell's inequalities[4]

$$-2 \leqslant S \leqslant 2, \tag{2}$$

where

$$S = E(\vec{a},\vec{b}) - E(\vec{a},\vec{b}') + E(\vec{a}',\vec{b}) + E(\vec{a}',\vec{b}')$$

involves four measurements in four various orientations. On the other hand, for suitable sets of orientations,[4] the quantum mechanical predictions can reach the values $S = \pm 2\sqrt{2}$, in clear contradiction with (2): Quantum mechanics cannot be completed by an underlying structure such as "realistic local theories."

Several experiments with increasing accuracy have been performed, and they clearly favor quantum mechanics.[3,5] Unfortunately, none allowed a direct test using inequalities (2), since none followed the scheme of Fig. 1 closely enough. Some experiments were performed with pairs of photons (or of protons). But no efficient analyzers are available at such energies, and the results that would have been obtained with ideal polarizers are deduced indirectly from Compton scattering experiments. The validity of such a procedure in the context of Bell's theorem has been criticized.[3,6]

There are also experiments with pairs of low-energy photons emitted in atomic radiative cascades. True polarizers are available in the visible range. However, all previous experiments involved single-channel analyzers, transmitting one polarization ($\vec{a}$ or $\vec{b}$) and blocking the orthog-

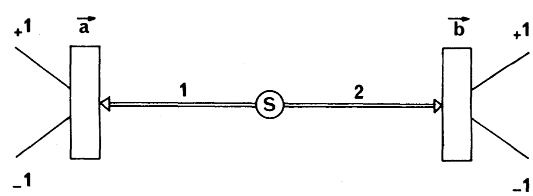

FIG. 1. Einstein-Podolsky-Rosen-Bohm *gedankenexperiment.* Two-spin-$\frac{1}{2}$ particles (or photons) in a singlet state (or similar) separate. The spin components (or linear polarizations) of 1 and 2 are measured along $\vec{a}$ and $\vec{b}$. Quantum mechanics predicts strong correlations between these measurements.

onal one. The measured quantities were thus only the coincidence rates in +1 channels: $R_{++}(\vec{a}, \vec{b})$. Several difficulties then arise[3] as a result of the very low efficiency of the detection system (the photomultipliers have low quantum efficiencies and the angular acceptance is small). The measurements of polarization are inherently incomplete: When a pair has been emitted, if no count is obtained at one of the photomultipliers, there is no way to know whether it has been missed by the (low-efficiency) detector or whether it has been blocked by the polarizer (only the latter case would be a real polarization measurement). Thus, coincidence counting rates such as $R_{+-}(\vec{a}, \vec{b})$ or $R_{--}(\vec{a}, \vec{b})$ cannot be measured directly. It is nevertheless possible to derive from the experimental data numerical quantities which can (according to quantum mechanics) possibly violate Bell-type inequalities. For this purpose, one has to resort to auxiliary experiments, where coincidence rates are measured with one or both polarizers removed. Some reasoning, with a few additional—and very natural—assumptions (such as the "no-enhancement" assumption of Clauser and Horne[7]), then allows one to obtain actually operational inequalities.

In this Letter, we report the results of an experiment following much more closely the ideal scheme of Fig. 1. True dichotomic polarization measurements on visible photons have been performed by replacing ordinary polarizers by two-channel polarizers, separating two orthogonal linear polarizations, followed by two photomultipliers (Fig. 2). The polarization measurements then become very similar to usual Stern-Gerlach measurements for spin-$\frac{1}{2}$ particles.[8]

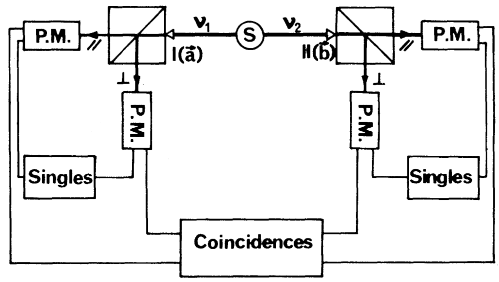

FIG. 2. Experimental setup. Two polarimeters I and II, in orientations $\vec{a}$ and $\vec{b}$, perform true dichotomic measurements of linear polarization on photons ν_1 and ν_2. Each polarimeter is rotatable around the axis of the incident beam. The counting electronics monitors the singles and the coincidences.

Using a fourfold coincidence technique, we measure in a single run the four coincidence rates $R_{\pm\pm}(\vec{a}, \vec{b})$, yielding directly the correlation coefficient for the measurements along $\vec{a}$ and $\vec{b}$:

$$E(\vec{a}, \vec{b}) = \frac{R_{++}(\vec{a}, \vec{b}) + R_{--}(\vec{a}, \vec{b}) - R_{+-}(\vec{a}, \vec{b}) - R_{-+}(\vec{a}, \vec{b})}{R_{++}(a, b) + R_{--}(a, b) + R_{+-}(a, b) + R_{-+}(a, b)}. \tag{3}$$

It is then sufficient to repeat the same measurements for three other choices of orientations, and inequalities (2) can directly be used as a test of realistic local theories versus quantum mechanics. This procedure is sound if the measured values (3) of the correlation coefficients can be taken equal to the definition (1), i.e., if we assume that the ensemble of actually detected pairs is a faithful sample of all emitted pairs. This assumption is highly reasonable with our very symmetrical scheme, where the two measurement results +1 and −1 are treated in the same way (the detection effiencies in both channels of a polarizer are equal). All data are collected in very similar experimental conditions, the only changes being rotations of the polarizers.

Such a procedure allows us not only to suppress possible systematic errors (e.g., changes occurring when removing the polarizers) but also to control more experimental parameters. For instance, we have checked that the sum of the coincidence rates of one photomultiplier with both photomultipliers on the other side is constant. We have also observed that the sum of the four coincidence rates $R_{\pm\pm}(\vec{a}, \vec{b})$ is constant when changing the orientations; thus the size of the selected sample is found constant.

We have used the high-efficiency source previously described.[5] A $(J=0)\rightarrow(J=1)\rightarrow(J=0)$ cascade in calcium-40 is selectively excited by two-photon absorption, with use of two single-mode lasers. Pairs of photons (at wavelengths $\lambda_1 = 551.3$ nm and $\lambda_2 = 422.7$ nm) correlated in polarization are emitted at a typical rate of 5×10^7 s^{-1}. The polarizers are polarizing cubes (Fig. 2) made of two prisms with suitable dielectric thin films on the sides stuck together; the faces are antirefelction coated. Cube I transmits light polarized in the incidence plane onto the active hypotenuse (parallel polarization, along $\vec{a}$) while it reflects the orthogonal polarization (perpendicular polarization). Cube II works similarly. For actual polarizers we define transmission and reflection coefficients: $T^{\parallel}$ and $R^{\perp}$ are close to 1, while $T^{\perp}$ and $R^{\parallel}$ are close to 0. The measured values of our devices are $T_1^{\parallel}=R_1^{\perp}=0.950$ and $T_1^{\perp}=R_1^{\parallel}=0.007$ at λ_1; $T_2^{\parallel}=R_2^{\perp}=0.930$ and $T_2^{\perp}=R_2^{\parallel}=0.007$ at λ_2 (all values are ± 0.005). Each polarizer is mounted in a rotatable mechanism holding two photomultipliers; we call the ensemble a polarimeter. The gains of the two photomultipliers are adjusted for the equality of the counting detection efficiencies in both channels of a polarimeter (2×10^{-3} at 422 nm, 10^{-3} at 551 nm). Typical single rates (over 10^4 s^{-1}) are high compared with dark rates (10^2 s^{-1}). Wavelength filters at 422 or 551 nm are mounted in front of each photomultiplier. The fourfold coincidence electronics includes four overlap-type coincidence circuits. Each coincidence window, about 20 ns wide, has been accurately measured. Since they are large compared to the lifetime of the intermediate state of the cascade (5 ns) all true coincidences are registered. We infer the accidental coincidence rates from the corresponding single rates, knowing the widths of the windows. This method is valid with our very stable source, and it has been checked by comparing it with the methods of Ref. 5, using delayed coincidence channels and/or a time-to-amplitude converter. By subtraction of these accidental rates (about 10 s^{-1}) from the total rates, we obtain the true coincidence rates $R_{\pm\pm}(\vec{a},\vec{b})$ (actual values are in the range 0–40 s^{-1}, depending on the orientations). A run lasts 100 s, and $E(\vec{a},\vec{b})$ derived from Eq. (3) is measured with a typical statistical accuracy of ± 0.02 (the sum of the four coincidence rates is typically 80 s^{-1}).

It is well known that the greatest conflict between quantum mechanical predictions and the inequalities (2) is expected for the set of orientations $(\vec{a},\vec{b})=(\vec{b},\vec{a}')=(\vec{a}',\vec{b}')=22.5°$ and $(\vec{a},\vec{b}')=67.5°$. Five runs have been performed at each of these orientations; the average yields

$$S_{\rm expt}=2.697\pm0.015. \quad (4)$$

The indicated uncertainty is the standard deviation accounting for the Poisson law in photon counting. The impressive violation of inequalities (2) is 83% of the maximum violation predicted by quantum mechanics with ideal polarizers (the largest violation of generalized Bell's inequalities previously reported was 55% of the predicted violation in the ideal case[5]).

With symmetrical polarimeters, quantum mechanics predicts

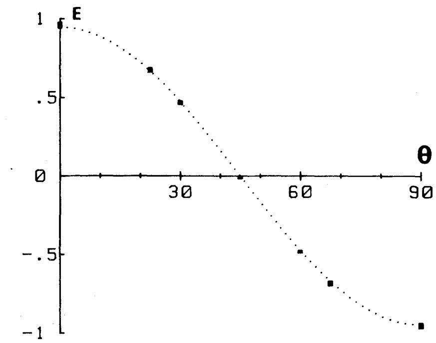

FIG. 3. Correlation of polarizations as a function of the relative angle of the polarimeters. The indicated errors are ± 2 standard deviations. The dotted curve is not a fit to the data, but quantum mechanical predictions for the actual experiment. For ideal polarizers, the curve would reach the values ± 1.

$$E(\vec{a},\vec{b})=F\frac{(T_1^{\parallel}-T_1^{\perp})(T_2^{\parallel}-T_2^{\perp})}{(T_1^{\parallel}+T_1^{\perp})(T_2^{\parallel}+T_2^{\perp})}\cos 2(\vec{a},\vec{b}). \quad (5)$$

($F=0.984$ in our case; it accounts for the finite solid angles of detection.) Thus, for our experiment,

$$S_{\rm QM}=2.70\pm0.05. \quad (6)$$

The indicated uncertainty accounts for a slight lack of symmetry between both channels of a polarimeter: We have found a variation of $\pm 1\%$ of the detection efficiencies when rotating the polarimeters. This spurious effect has been explained as small displacements of the light beam impinging onto the photocathode. The effect of these variations on the quantum mechanical predictions has been computed, and cannot create a variation of $S_{\rm QM}$ greater than 2%.[9]

Figure 3 shows a comparison of our results with the predictions of quantum mechanics. Here, for each relative orientation $\theta=(\vec{a},\vec{b})$, we have averaged several measurements in different absolute orientations of the polarimeters; this procedure averages out the effect of the slight variations of the detection efficiencies with orientation. The agreement with quantum mechanics is better than 1%.

In conclusion, our experiment yields the strongest violation of Bell's inequalities ever achieved, and excellent agreement with quantum mechanics. Since it is a straightforward transposition of the ideal Einstein-Podolsky-Rosen-Bohm scheme, the experimental procedure is very simple, and needs no auxiliary measurements as in previous experiments with single-channel polarizers. We are thus led to the rejection of realistic local theories if we accept the assumption that there is no bias in the detected samples: Experiments support this natural assumption.

Only two loopholes remain open for advocates of realistic theories without action at a distance.[10] The first one, exploiting the low efficiencies of detectors, could be ruled out by a feasible experiment.[11] The second one, exploiting the static character of all previous experiments, could also be ruled out by a "timing experiment" with variable analyzers[12] now in progress.

The authors acknowledge many valuable discussions with F. Laloë about the principle of this experiment. They are grateful to C. Imbert who sponsors this work.

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[8]Such an experimental scheme has been proposed and discussed by several authors: A. Shimony, in *Foundations of Quantum Mechanics*, edited by B. d'Espagnat (Academic, New York, 1972); F. Laloë, private communication; A. Garuccio and V. Rapisarda, Nuovo Cimento A65, 269 (1981); see also Ref. 7. A similar experiment has been undertaken by V. Rapisarda *et al.*

[9]Alternatively, this lack of symmetry can be taken into account in generalized Bell's inequalities similar to inequalities (2). (The demonstration will be published elsewhere.) In our case, the inequalities then become $|S| \leq 2.08$. The violation is still impressive.

[10]As in our previous experiments, the polarizers are separated by 13 m. The detection events are thus spacelike separated, and we eliminate the loophole considered by L. Pappalardo and V. Rapidarda, Lett. Nuovo Cimento 29, 221 (1980).

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Experimental Test of Bell's Inequalities Using Time-Varying Analyzers

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Correlations of linear polarizations of pairs of photons have been measured with time-varying analyzers. The analyzer in each leg of the apparatus is an acousto-optical switch followed by two linear polarizers. The switches operate at incommensurate frequencies near 50 MHz. Each analyzer amounts to a polarizer which jumps between two orientations in a time short compared with the photon transit time. The results are in good agreement with quantum mechanical predictions but violate Bell's inequalities by 5 standard deviations.

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Bell's inequalities apply to any correlated measurement on two correlated systems. For instance, in the optical version of the Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*,[1] a source emits pairs of photons (Fig. 1). Measurements of the correlations of linear polarizations are performed on two photons belonging to the same pair. For pairs emitted in suitable states, the correlations are strong. To account for these correlations, Bell[2] considered theories which invoke common properties of both members of the

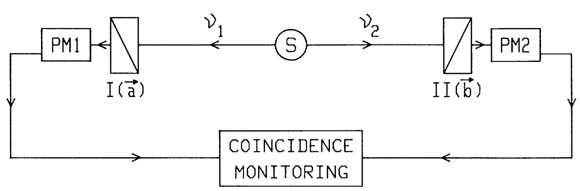

FIG. 1. Optical version of the Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*. The pair of photons ν_1 and ν_2 is analyzed by linear polarizers I and II (in orientations $\vec{a}$ and $\vec{b}$) and photomultipliers. The coincidence rate is monitored.

pair. Such properties are referred to as supplementary parameters. This is very different from the quantum mechanical formalism, which does not involve such properties. With the addition of a reasonable locality assumption, Bell showed that such classical-looking theories are constrained by certain inequalities that are not always obeyed by quantum mechanical predictions.

Several experiments of increasing accuracy[3-5] have been performed and clearly favor quantum mechanics. Experiments using pairs of visible photons emitted in atomic radiative cascades seem to achieve a good realization of the ideal *Gedankenexperiment*.[5] However, all these experiments have been performed with static setups, in which polarizers are held fixed for the whole duration of a run. Then, one might question Bell's locality assumption, that states that the results of the measurement by polarizer II does not depend on the orientation $\vec{a}$ of polarizer I (and vice versa), nor does the way in which pairs are emitted depend on $\vec{a}$ or $\vec{b}$. Although highly reasonable, such a locality condition is not prescribed by any fundamental physical law. As pointed out by Bell,[2] it is possible, in such experiments, to reconcile supplementary-parameter theories and the experimentally verified predictions of quantum mechanics: "The settings of the instruments are made sufficiently in advance to allow them to reach some mutual rapport by exchange of signals with velocity less than or equal to that of light." If such interactions existed, Bell's locality condition would no longer hold for static experiments, nor would Bell's inequalities.

Bell thus insisted upon the importance of "experiments of the type proposed by Bohm and Aharonov,[6] in which the settings are changed during the flight of the particles." In such a "timing experiment," the locality condition would then become a consequence of Einstein's causality, preventing any faster-than-light influence.

In this Letter, we report the results of the first experiment using variable polarizers. Following our proposal,[7] we have used a modified scheme (Fig. 2). Each polarizer is replaced by a setup involving a switching device followed by two polarizers in two different orientations: $\vec{a}$ and $\vec{a}'$ on side I, and $\vec{b}$ and $\vec{b}'$ on side II. Such an optical switch is able to rapidly redirect the incident light from one polarizer to the other one. If the two switches work at random and are uncorrelated, it is possible to write generalized Bell's inequalities in a form similar to Clauser-Horne-

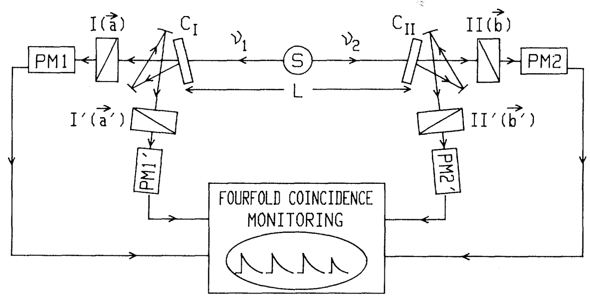

FIG. 2. Timing experiment with optical switches. Each switching device ($C_{\rm I}, C_{\rm II}$) is followed by two polarizers in two different orientations. Each combination is equivalent to a polarizer switched fast between two orientations.

Shimony-Holt inequalities[8]:

$$-1 \leq S \leq 0,$$

with

$$S = \frac{N(\vec{a},\vec{b})}{N(\infty,\infty)} - \frac{N(\vec{a},\vec{b}')}{N(\infty,\infty')} + \frac{N(\vec{a}',\vec{b})}{N(\infty',\infty)} + \frac{N(\vec{a}',\vec{b}')}{N(\infty',\infty')} - \frac{N(\vec{a}',\infty)}{N(\infty',\infty)} - \frac{N(\infty,\vec{b})}{N(\infty,\infty)}.$$

The quantity S involves (i) the four coincidence counting rates [$N(\vec{a},\vec{b})$, $N(\vec{a}',\vec{b})$, etc.] measured in a *single run;* (ii) the four corresponding coincidence rates [$N(\infty,\infty)$, $N(\infty',\infty)$, etc.] with all polarizers removed; and (iii) two coincidence rates [$N(\vec{a}',\infty)$, $N(\infty,\vec{b})$] with a polarizer removed on each side. The measurements (ii) and (iii) are performed in auxiliary runs.

In this experiment, switching between the two channels occurs about each 10 ns. Since this delay, as well as the lifetime of the intermediate level of the cascade (5 ns), is small compared to L/c (40 ns), a detection event on one side and the corresponding change of orientation on the other side are separated by a spacelike interval.

The switching of the light is effected by acousto-optical interaction with an ultrasonic standing wave in water.[9] As sketched in Fig. 3 the incidence angle is equal to the Bragg angle, $\theta_B = 5 \times 10^{-3}$ rad. It follows that light is either transmitted straight ahead or deflected at an angle $2\theta_B$. The light is completely transmitted when the amplitude of the standing wave is null, which occurs twice during an acoustical period. A quarter of a period later, the amplitude of the standing wave is maximum and, for a suitable value of the acoustical power, light is then fully

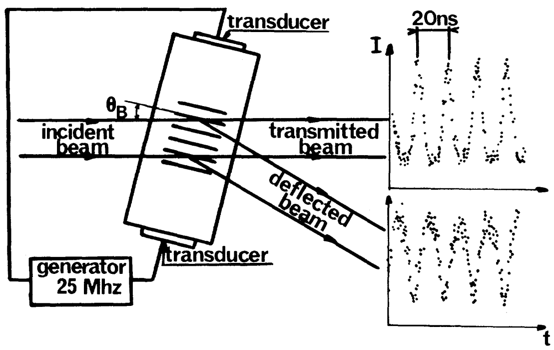

FIG. 3. Optical switch. The incident light is switched at a frequency around 50 MHz by diffraction at the Bragg angle on an ultrasonic standing wave. The intensities of the transmitted and deflected beams as a function of time have been measured with the actual source. The fraction of light directed towards other diffraction orders is negligible.

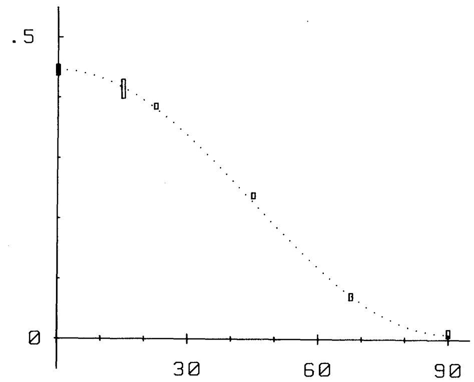

FIG. 4. Average normalized coincidence rate as a function of the relative orientation of the polarizers. Indicated errors are ±1 standard deviation. The dashed curve is not a fit to the data but the predictions by quantum mechanics for the actual experiment.

deflected. This optical switch thus works at twice the acoustical frequency.

The ultrasonic standing-wave results from interference between counterpropagating acoustic waves produced by two electroacoustical transducers driven in phase at about 25 MHz. In auxiliary tests with a laser beam, the switching has been found complete for an acoustical power about 1 W. In the actual experiment, the light beam has a finite divergence, and the switching is not complete (Fig. 3).

The other parts of the experiment have already been described in previous publications.[4,5] The high-efficiency well-stabilized source of pairs of correlated photons, at wavelengths $\lambda_1 = 422.7$ nm and $\lambda_2 = 551.3$ nm, is obtained by two-photon excitation of a $(J=0) \rightarrow (J=1) \rightarrow (J=0)$ cascade in calcium.

Since each switch is 6 m from the source, rather complicated optics are required to match the beams with the switches and the polarizers. We have carefully checked each channel for no depolarization, by looking for a cosine Malus law when a supplementary polarizer is inserted in front of the source. These auxiliary tests are particularly important for the channels which involve two mirrors inclined at 11°. They also yield the efficiencies of the polarizers, required for the quantum mechanical calculations.

The coincidence counting electronics involve four double-coincidence-counting circuits with coincidence windows of 18 ns. For each relevant pair of photomultipliers, we monitor nondelayed and delayed coincidences. The true coincidence rate (i.e., coincidences due to photons emitted by the same atom) are obtained by subtraction. Simultaneously, a time-to-amplitude converter, followed by a fourfold multichannel analyzer, yields four time-delay spectrums. Here, the true coincidence rate is taken as the signal in the peak of the time-delay spectrum.[4]

We have not been able to achieve collection efficiencies as large as in previous experiments,[4,5] since we had to reduce the divergence of the beams in order to get good switching. Coincidence rates with the polarizers removed were only a few per second, with accidental coincidence rates about one per second.

A typical run lasts 12 000 s, involving totals of 4000 s with polarizers in place at a given set of orientations, 4000 s with all polarizers removed, and 4000 s with one polarizer removed on each side. In order to compensate the effects of systematic drifts, data accumulation was alternated between these three configurations about every 400 s. At the end of each 400-s period, the raw data were stored for subsequent processing with the help of a computer.

At the end of the run, we average the true coincidence rates corresponding to the same configurations for the polarizers. We then compute the relevant ratios for the quantity S. The statistical accuracy is evaluated according to standard statistical methods for photon counting. The processing is performed on both sets of data: that obtained with coincidence circuits, and that obtained with the time-to-amplitude converter. The two methods have always been found to be consistent.

Two runs have been performed in order to test Bell's inequalities. In each run, we have chosen a set of orientations leading to the greatest predicted conflict between quantum mechanics and Bell's inequalities $[(\vec{a},\vec{b})=(\vec{b},\vec{a}')=(\vec{a}',\vec{b}')=22.5°; (\vec{a},\vec{b}')=67.5°]$. The average of the two runs yields

$$S_{expt}=0.101\pm0.020,$$

violating the inequality $S\leq 0$ by 5 standard deviations. On the other hand, for our solid angles and polarizer efficiencies, quantum mechanics predicts $S_{QM}=0.112$.

We have carried out another run with different orientations, for a direct comparison with quantum mechanics. Figure 4 shows that the agreement is excellent.

The new feature of this experiment is that we change the settings of the polarizers, at a rate greater than c/L. The ideal scheme has not been completed since the change is not truly random, but rather quasiperiodic. Nevertheless, the two switches on the two sides are driven by different generators at different frequencies. It is then very natural to assume that they function in an uncorrelated way.

A more ideal experiment with random and complête switching would be necessary for a fully conclusive argument against the whole class of supplementary-parameter theories obeying Einstein's causality. However, our observed violation of Bell's inequalities indicates that the experimental accuracy was good enough for pointing out a hypothetical discrepancy with the predictions of quantum mechanics. No such effect was observed.[10]

This work has been carried out in the group of Professor Imbert, who we thank for his support. We thank all the technical staff of the Institut d'Optique, especially André Villing for the electronics. We are indebted to Jean-Pierre Passérieux, from the Département de Physique Nucléaire et Basse Energie at Centre d'Etudes National de Saclay, for his assistance in fast-coincidence techniques, and to Dr. Torguet and Dr. Gazalé, from Laboratoire d'Acoustooptique de Valenciennes, for help with the optical switches. We also acknowledge the valuable help of Philippe Grangier during the final runs.

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