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.

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 pho-

tons (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-
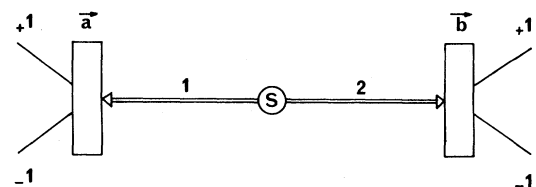

FIG. 1. Einstein-Podolsky-Rosen-Bohm *gedankenexperiment*. Two-spin-$\frac{1}{2}$ particles (or photons) in a singlet state (or similar) separate. The spin components (or linear polarizations) of 1 and 2 are measured along $\vec{a}$ and $\vec{b}$. Quantum mechanics predicts strong correlations between 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 efficien-
cies and the angular acceptance is small). The
measurements of polarization are inherently in-
complete: 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 wheth-
er it has been blocked by the polarizer (only the
latter case would be a real polarization meas-
urement). Thus, coincidence counting rates such
as $R_{+-}(\vec{a}, \vec{b})$ or $R_{--}(\vec{a}, \vec{b})$ cannot be measured di-
rectly. It is nevertheless possible to derive
from the experimental data numerical quantities
which can (according to quantum mechanics) pos-
sibly violate Bell-type inequalities. For this
purpose, one has to resort to auxiliary experi-
ments, where coincidence rates are measured
with one or both polarizers removed. Some rea-
soning, 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 ex-
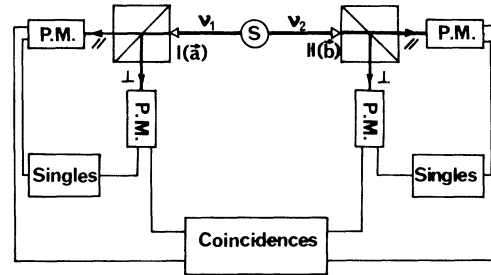periment following much more closely the ideal

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.

scheme of Fig. 1. True dichotomic polarization
measurements on visible photons have been per-
formed by replacing ordinary polarizers by two-
channel polarizers, separating two orthogonal
linear polarizations, followed by two photomul-
tipliers (Fig. 2). The polarization measure-
ments then become very similar to usual Stern-
Gerlach measurements for spin-$\frac{1}{2}$ particles.[8]

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 $\vec{b}$:

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

It is then sufficient to repeat the same measure-
ments 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 meas-
ured 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 meas-
urement results +1 and −1 are treated in the
same way (the detection effiencies in both chan-
nels of a polarizer are equal). All data are col-
lected 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 occur-
ring when removing the polarizers) but also to
control more experimental parameters. For in-
stance, we have checked that the sum of the coin-
cidence 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 pre-
viously described.[5] A $(J=0) \rightarrow (J=1) \rightarrow (J=0)$ cas-
cade in calcium-40 is selectively excited by two-
photon absorption, with use of two single-mode
lasers. Pairs of photons (at wavelengths λ_1
= 551.3 nm and λ_2 = 422.7 nm) correlated in po-
larization 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 (perpendicu-
lar polarization). Cube II works similarly. For
actual polarizers we define transmission and re-

flection 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

$$S_{\text{expt}} = 2.697 \pm 0.015. \tag{4}$$

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]).

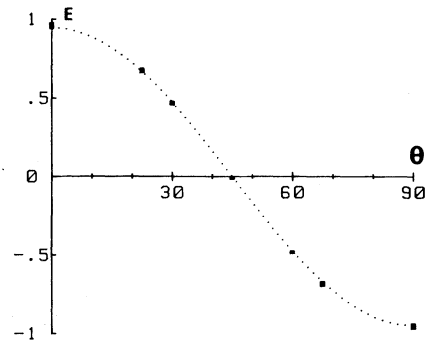With symmetrical polarimeters, quantum mech-

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.

anics predicts

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

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

$$S_{\text{QM}} = 2.70 \pm 0.05. \tag{6}$$

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_{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.

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[7] J. F. Clauser and M. A. Horne, Phys. Rev. D 10, 526 (1974).

[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 $|S| \le 2.08$. The violation is still impressive.

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Hopping Mechanism Generating 1/f Noise in Nonlinear Systems

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It is shown experimentally that a bistable system is driven by a suitable external modulation to a region of random intermittency which displays a low-frequency power-law divergence. This low-frequency divergence is associated with a topological alternation between two strange attractors in phase space, either unsymmetric or fully symmetric depending on whether the two potential valleys are differently or equally located. This picture seems sufficiently general to apply to most cases of low-frequency noise currently reported.

We show evidence of a mechanism responsible for low-frequency excess noise in a nonlinear system. The mechanism seems to be sufficiently general to be a possible explanation for many physical cases where excess, or 1/f, noise appears, even though we do not pretend to claim full universality.

In order to study the routes to chaos in nonlinear nonequilibrium physical systems we have built a suitable electronic oscillator with a cubic non-linearity imposed by a selected field-effect transistor device and driven by an external modulation. The internal force law corresponds to a two-valley potential. The dynamical equation for the normalized oscillator output $x(t)$ is

$$\frac{d^2x}{d\tau^2} + k\frac{dx}{d\tau} - x + 4x^3 = A \cos\omega\tau, \tag{1}$$

where $\tau = \omega_0 t$, ω_0 is the oscillator frequency, ω is the modulation frequency normalized to ω_0,