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Einstein-Podolsky-Rosen-Bohm Experiment Using Pairs of Light Quanta Produced by Type-II Parametric Down-Conversion

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We report a new two-photon polarization correlation experiment for realizing the Einstein-Podolsky-Rosen-Bohm (EPRB) state and for testing Bell-type inequalities. We use the pair of orthogonally polarized light quanta generated in type-II parametric down-conversion. In a 1 nm bandwidth, we observe from the output of a 0.5 mm β-BaB_2O_4 crystal the EPRB correlations in coincidence counts, and measure an associated Bell inequality violation of 22 standard deviations.

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The Einstein-Podolsky-Rosen-Bohm (EPRB) gedanken experiments [1,2] for two quantum particles has played an important conceptual role for viewing quantum-mechanical correlations that provide an intriguing challenge to classical intuition. In brief, the EPRB correlation considered here is contained in a two-particle, two detector setup in which a measurement is first made on one particle at one detector of a parameter that is indeterminate prior to the measurement. This outcome then implies with certainty the outcome of the measurement on the second particle. Demonstrations for spin-$\frac{1}{2}$ quanta [3], for photon polarization states [3–8], and more recently for other variables [9–12] have all shown these EPRB correlations in the coincidence registrations of two detectors.

The same quantum-mechanical state of two particles that generates an EPRB experiment also provides an enhancement of observed coincidence rates beyond a maximum bound set by Bell's two postulates [3,13]. Violations of Bell-type inequalities are one application of EPRB states.

We have found a new and convenient way to generate quantum states that exhibit these EPRB correlations [1,2], with an associated violation of two-particle Bell-type inequalities [3,13]. Our source is the pair of light quanta generated in parametric down-conversion with type-II phase matching. The pair is incident on one port of a nonpolarizing beam splitter with output ports containing two linear analyzer-detector packages. Our Bell inequality violation in polarization variables is as large as 22 standard deviations.

In contrast to type-I phase matching, the output pair of down-conversion in type-II phase matching is already orthogonally polarized, since one parametrically generated quantum travels as an ordinary (o) ray and the other as an extraordinary (e) ray in the birefringent medium. We therefore identify the type-II phase matching process as a natural source of two orthogonal linear polarizations. These photon pairs are produced at the nonlinear crystal, with the usual phase matching relations

$$\omega_s+\omega_i=\omega_p,\quad \mathbf{k}_s+\mathbf{k}_i=\mathbf{k}_p\,, \tag{1}$$

linking pump (p), signal (s), and idler (i) modes.

A comparison can be made to photon polarization Bell inequality violations using type-I phase matching [7,8]. In those studies, the noncollinear signal and idler outputs pass through an interferometer with a half-wave retardation plate in one arm to generate the state

$$|\Psi\rangle_{2\gamma}\propto[|\hat{\mathbf{x}}\rangle_1|\hat{\mathbf{y}}\rangle_2+|\hat{\mathbf{y}}\rangle_1|\hat{\mathbf{x}}\rangle_2]\,, \tag{2}$$

where subscripts refer to detector number. This is a photon polarization analog of the spin-$\frac{1}{2}$ singlet state. As we shall demonstrate, no waveplate or interferometer is required for the type-II state to generate the state of form

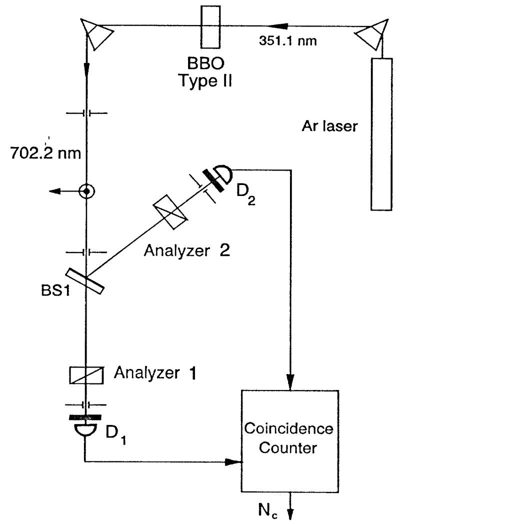

FIG. 1. Experimental setup. Pairs from collinear type-II down-conversion in a BBO crystal are separated from the pump at a prism and directed to a 50:50 beam splitter. The coincidence registrations in detectors 1 and 2 are recorded as a function of the angles θ_1 and θ_2 of the Glan-Thompson analyzers, for each bandwidth filter installed in front of the detectors.

(2).

Our experimental configuration is shown in Fig. 1. A 351.1 nm unfocused argon ion laser line is incident on a 0.5 mm long BaB_2O_4 (BBO) crystal oriented to achieve type-II phase matching in parametric down-conversion, with the 702.2 nm wavelength collinear with the pump. Pairs degenerate in propagation direction and frequency emerge from the BBO crystal and separate from the pump at a quartz prism. They are split at a nonpolarizing beam splitter and sent to two Glan-Thompson ana-

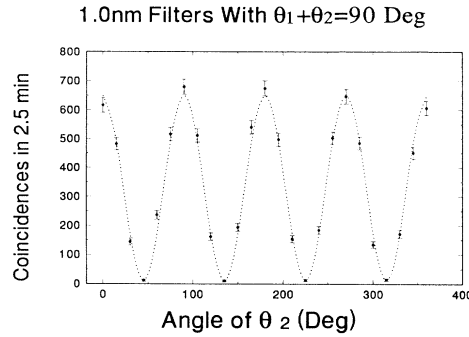

FIG. 2. Measurements of coincidences in our setup with the constraint $\theta_1+\theta_2=90°$ enforced between the two Glan-Thompson analyzer angles. The prediction of (6) for $\lambda=1.98\pm0.04$ is also shown.

lyzer-detector packages. Coincidence counts are collected in a 6 nsec coincidence time window from two avalanche photodiode detectors operating in the Geiger mode.

An analysis of the quantum state shows the expected dependence of the coincidences on the analyzer angles (θ_1,θ_2) at detectors 1 and 2, respectively. We write the down-conversion state exiting the crystal in the standard form

$$|\Psi\rangle_{2\gamma}=\int d\omega_s\Phi(\omega_s)|\omega_s,\hat{\mathbf{o}}\rangle|\omega_p-\omega_s,\hat{\mathbf{e}}\rangle\,, \tag{3}$$

specifying an o ray of frequency ω_s and an e ray of frequency $\omega_p-\omega_s$. For a fixed crystal orientation, the phase matching relations (1) are satisfied for a range of frequencies, specified by the integration over ω_s with distribution function $\Phi(\omega_s)$.

After a nonpolarizing beam splitter, this two-photon ket generates coincidences from terms

$$|\Psi\rangle_{12}=\int d\omega_s\Phi(\omega_s)(\sqrt{RT})[-|\omega_s,\hat{\mathbf{x}}\rangle_1|\omega_p-\omega_s,\hat{\mathbf{y}}\rangle_2+|\omega_s,\hat{\mathbf{x}}\rangle_2|\omega_p-\omega_s,\hat{\mathbf{y}}\rangle_1]\,, \tag{4}$$

where the subscript 1,2 refers to output port, or detector number (see Fig. 1), and the $\hat{\mathbf{x}}$ direction (corresponding to $\theta=0$) is chosen to align with $\hat{\mathbf{o}}$. The minus sign in (4) comes from the inversion upon reflection of one of the two transverse axes $(\hat{\mathbf{x}},\hat{\mathbf{y}})$ to preserve a right-handed coordinate system with respect to the $\hat{\mathbf{k}}$ direction. The intensity reflection (R_x,R_y) and transmission (T_x,T_y) coefficients were measured to obey the relations $R_x=R_y\equiv R, T_x=T_y\equiv T$ within 2%.

After passage through linear analyzers oriented at θ_1 and θ_2, this state predicts a quantum-mechanical coincidence probability

$$P_{12}\propto\left|\int d\omega_s\Phi(\omega_s)(-\cos\theta_1\sin\theta_2 e^{-i\omega_s t_1}e^{-i(\omega_p-\omega_s)t_2}+\sin\theta_1\cos\theta_2 e^{-i\omega_s t_2}e^{-i(\omega_p-\omega_s)t_1})\right|^2, \tag{5}$$

where plane wave forms are used for the o- or e-ray modes incident on detector i at times t_i^α for $i=1,2$. Coincidence counts collected in a large time window are

$$N_{12}=N_0[\cos^2\theta_1\sin^2\theta_2+\sin^2\theta_1\cos^2\theta_2-\lambda\sin\theta_1\cos\theta_1\sin\theta_2\cos\theta_2]\,, \tag{6}$$

for a constant N_0 and parameter λ given by

$$\lambda=\frac{\langle\Psi(t_1,t_2)\Psi^*(t_2,t_1)\rangle+\text{c.c.}}{\langle|\Psi(t_1,t_2)|^2\rangle}\,, \tag{7}$$

where

$$\Psi(t_1,t_2)\equiv\int d\omega_s\Phi(\omega_s)e^{-i\omega_s t_1}e^{-i(\omega_p-\omega_s)t_2}\,,$$

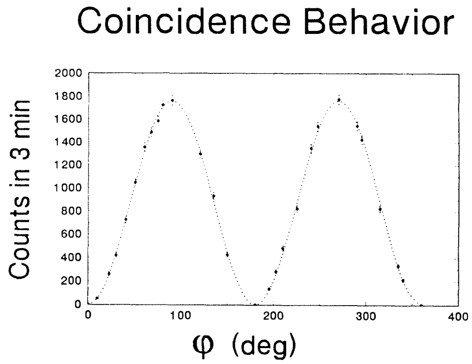

FIG. 3. Measurements of coincidences in our setup as a function of $\phi \equiv \theta_1 - \theta_2$, for fixed $\theta_1 = 45°$ and variable θ_2.

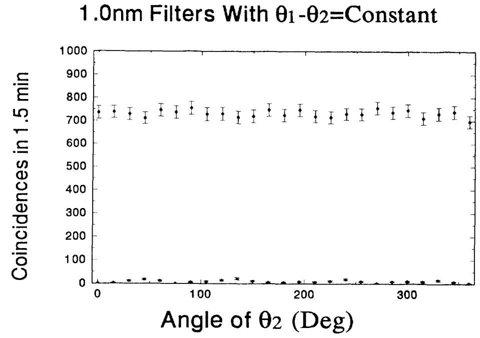

FIG. 4. Coincidences obtained for $\lambda=2$ with the constraint $\theta_1 - \theta_2$=const enforced between the two Glan-Thompson analyzer angles, for two values of the constant: 0° and 90°.

and $\langle\rangle$ denotes an integration over the time window. The strength of the cross terms, specified by λ, was experimentally measured by mapping out the coincidence behavior as a function of θ_1 and θ_2. The most informative tests were systematic studies for which $\theta_1 = 45°$ or $\theta_1 \pm \theta_2 = 90°$. Figures 2–4 summarize the results of these investigations.

The form (7) is not *a priori* equal to 2 for arbitrary $\Psi(t_1,t_2)$ [i.e., for arbitrary $\Phi(\omega_s)$]. Indeed, for filters of bandpass greater than 1 nm, or for a BBO crystal of greater length (5.65 mm), λ was found to be less than 2. We discuss this bandwidth and crystal length dependence elsewhere in greater detail. For the present conditions (filters with FWHM of 1 nm, crystal length 0.5 mm), the large visibility ($>99\%$) in Figs. 2 and 3 is predicted from (6) only for λ nearly 2. Least squares fits to Figs. 2 and 3 generated $\lambda = 1.98 \pm 0.04$.

This value of λ is within 1σ of 2, for which (5) reduces to $\sin^2(\theta_1 - \theta_2)$, a function of only the difference angle, $\theta_1 - \theta_2$ (see Fig. 4). This dependence on only one variable specifies an invariance with respect to the other, often referred to as a rotational invariance [3,7]. Here, unlike type-I Bell inequality violations [7,8], the coincidence counts depend on the difference angle of the analyzers, rather than the sum angle, due to the relative minus sign in (4) as compared with the plus sign in (2). This clarifies a potential misconception that the sum angle is necessarily associated with bosons, and the difference angle with fermions. This is the first experiment in which the minus sign appears for photon polarization, not because of an underlying symmetry property, but rather because here both photons are incident on the same side of the beam splitter.

This rotational invariance guarantees the existence of a correlation of the EPRB type. Either the *o* ray or the *e* ray could trigger either detector, making detection of single counts ideally independent of analyzer angle. Once one detector has fired, the conditional probability of registering an event in the second detector is given by the coincidence probability, which for $\lambda=2$ can be rewritten as $\propto \cos^2(\theta_1 - \theta_2 + 90°)$. This is Malus' law for detection of a linear polarization at angle $\theta_1 - \theta_2 + 90°$. The polarization at the second detector is known with certainty to be linear at this angle after the first detector has fired. This is a correlation of the EPRB type.

The λ-dependent mixing term in (6) foils any interpretation specifying the *o* ray to be localized at detector 1 and the *e* ray at detector 2, or vice versa. Both of these quantum-mechanical amplitudes are present in (5), and their interference generates the λ-dependent term of (6) that represents an overlap of "*o* ray resolved at D_1, *e* ray resolved at D_2" ($\sim\cos\theta_1 \sin\theta_2$) with "*e* ray at D_1, *o* ray at D_2" ($\sim\sin\theta_1\cos\theta_2$).

Our remaining purpose is to use the coincidence count expression (6) to exhibit Bell inequality violations. This application of (6) proceeds without any necessary regard to the underlying mechanism producing the interference term.

For the $\lambda=2$ singlet state analog, we measured the Bell inequality expression as derived by Freedman [3,14]

$$\left|\frac{N_{12}(\phi) - N_{12}(3\phi)}{N_{12}(-,-)}\right| \leq 0.25\,, \tag{8}$$

for $\phi \equiv \theta_1 - \theta_2 = 22.5°$ (see Table I). Here $N_{12}(-,-)$ represents coincidence counts with both analyzers removed. The value of 0.25 in (8) is a bound on behavior dictated by any theory obeying Bell's two postulates of locality and reality that could be posed as an alternative to quantum mechanics in predicting the coincidence counts [3,13]. The quantum prediction for (8), for a singlet state analog and 100% efficient analyzers, is $0.25\sqrt{2} \approx 0.354$. Our average of four runs (Table I) in an accumulation time of 12 min for each entry in Table I yields a

TABLE I. Bell inequality measurements for $\phi = 22.5°$.

θ_1	$N(\phi)$	$N(3\phi)$	$N(-,-)$	Eq. (8)	
0°	1052	6054	16048	0.3117	± 0.0058
0°	1033	5931	15482	0.3164	± 0.0059
45°	902	5718	14915	0.3229	± 0.0061
45°	877	5424	14468	0.3143	± 0.0061

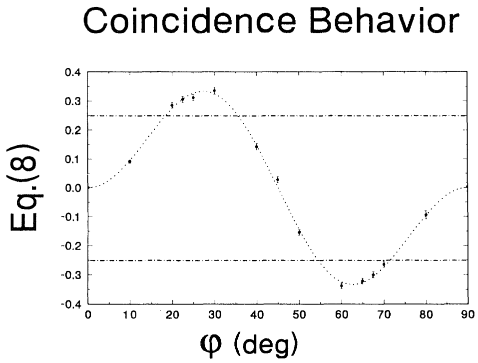

FIG. 5. The function of (8). Also shown is the singlet state prediction multiplied by the efficiency losses $\eta_1 \times \eta_2$ of the analyzers.

value $0.316 \pm 0.003(1\sigma)$, less than the perfect quantum prediction because of passive, polarization-independent losses at the analyzer faces, which were not optimally coated for the 702 nm wavelength. The efficiencies η_1, η_2 of analyzers 1 and 2 (0.905 ± 0.014 and 0.976 ± 0.015, respectively) are used to generate the quantum-mechanical prediction of (8) of 0.312 ± 0.018, in agreement with the observed value.

Symmetry properties about the system that were used [3,14] to derive (8) were demonstrated. Coincidences with one analyzer removed should be independent of the orientation of the other, and singles in each detector should be independent of analyzer angle. We verified each of these symmetry properties to within a few percent. The uncertainty of the quantum prediction is limited by the quadrature combination (5.8%) of uncertainties of all four symmetry properties. Here, as in other Bell inequality work [3–6], the precision of the measurement is greater than the uncertainty of the quantum prediction.

As a further integrity check, we plotted the function of (8) for arbitrary ϕ (Fig. 5). Also shown is the prediction generated from (6) using our values of η_1 and η_2. Of interest is that the physically relevant points at $\phi = 22.5°$, $67.5°$ for which the form is a Bell inequality statement are not at the maximum values of the function.

It is possible to avoid exhibiting the aforementioned symmetry properties used to derive (8) by testing a more general Bell inequality form. We proceed from the inequality [3,8,15]

$$[-N_{12}(\theta_1',\theta_2')+N_{12}(\theta_1',\theta_2)+N_{12}(\theta_1,\theta_2')+N_{12}(\theta_1,\theta_2)]-[N_{12}(\theta_1,-)+N_{12}(-,\theta_2)] \le 0\,, \tag{9}$$

in which the Clauser-Horne no-enhancement assumption [15] has already been imposed, and in which probabilities have been converted to coincidence counts N_{12} accumulated in some time interval.

Although we have generated violations of (9), we advocate a stronger version in which the transmission losses of the analyzers are recognized and removed. The basis for this is a generalized version of the no-enhancement hypothesis, in which the passive, polarization-independent analyzer losses are assumed not to affect the behavior of the source whose coincidence properties are under study. We note that these analyzer losses must be controlled [3,15,16] in a rigorous Bell inequality test. For our purpose here of exhibiting the coincidence behavior of the source, we use this generalization to alter (9) to the form

$$[-N_{12}(\theta_1',\theta_2')+N_{12}(\theta_1',\theta_2)+N_{12}(\theta_1,\theta_2')+N_{12}(\theta_1,\theta_2)]-[\eta_2 N_{12}(\theta_1,-)+\eta_1 N_{12}(-,\theta_2)] \le 0\,. \tag{10}$$

We deduced a choice of four angles ($\theta_1 = 22.5°$, $\theta_2 = 135°$, $\theta_1' = 67.5°$, $\theta_2' = 90°$) that would violate (9) or (10) maximally. Coincidence counts (Table II) in 8 min are collected for these angles. Table III shows the deduced violation in these counts of both (9) and (10).

As has been noted [8], violations of (10) occur for any greater-than-zero value of the left-hand side. For a relevant figure of merit in judging Bell inequality violations, we advocate the quantity $Q-1$, for Q the ratio of the term of (10) in square brackets to the term in parentheses. For $Q-1>0$, the form (10) is violated. We compare in Table III the measured $Q-1$ to the prediction generated from λ. As another consistency check, we list the ratio $\eta_2 N_{12}(\theta_1,-):\eta_1 N_{12}(-,\theta_2)$, which should be 1:1, within experimental error.

TABLE II. Bell inequality measurements.

$N(\theta_1',\theta_2')$	$N(\theta_1',\theta_2)$	$N(\theta_1,\theta_2)$	$N(\theta_1,\theta_2')$	$N(\theta_1,-)$	$N(-,\theta_2)$
951	4060	3701	4054	4534	5060

In conclusion, we have identified a new source useful in realizing the EPRB gedanken experiments and in testing Bell inequalities. We achieve the EPRB correlations by virtue of a coincidence probability $\propto \sin^2\phi$ for $\phi = \theta_1 - \theta_2$. We obtain a violation of the form (8) for polarization variables that is 22 standard deviations and limited here only by accumulation time. The state (5) is entangled [17] in polarization variables, leading to an interference term in coincidence counts that, because of EPRB corre-

TABLE III. Bell inequality violations using counts of Table II.

Eq. (9)	Eq. (10)	$\eta_2 \times N(\theta_1,-)$	$\eta_1 \times N(-,\theta_2)$	$Q-1$	$Q_{\rm pred}-1$
1188	1778	4425	4579	0.198	0.207
± 143	± 178	± 97	± 98	± 0.022	± 0.010
(8σ)	(10σ)				

lations and Bell-type inequality violations, is manifestly quantum in nature.

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