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

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(Received 23 May 1988)

A pair of correlated light quanta of 532-nm wavelength with the same linear polarization but divergent directions of propagation was produced by nonlinear optical parametric down conversion. Each light quantum was converted to a definite polarization eigenstate and was reflected by a turning mirror to superpose with the other at a beam splitter. For coincident detection at separated detectors, polarization correlations of the Einstein-Podolsky-Rosen-Bohm type were observed. We also observed a violation of Bell's inequality by 3 standard deviations.

Einstein, Podolsky, and Rosen[1] (EPR) proposed a gedanken experiment to argue that quantum mechanics is incomplete. The EPR gedanken experiment was based on the argument that noncommuting observables can have simultaneous reality in a gedanken quantum system with a correlated pair of particles. EPR first gave their criterion: "If, without in any way disturbing the system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of reality corresponding to this physical quantity." The well-known EPR gedanken experiment was later modified by Bohm.[2] A singlet state of two spin-$\frac{1}{2}$ particles is produced by some source,

$$|\psi\rangle = \frac{1}{\sqrt{2}} [\, |\hat{n}_1^+\rangle \otimes |\hat{n}_2^-\rangle - |\hat{n}_1^-\rangle \otimes |\hat{n}_2^+\rangle \,],$$

where the $|\hat{n}_i^{\pm}\rangle$ quantum mechanically describe a state in which particle 1 or 2 has spin "up" or "down," respectively, along the direction $\hat{n}$. Suppose one sets up his experiment to measure the spin of particle 1 along the x direction, then particle 2 will immediately be found to have its spin antiparallel to the x direction if the x component of its spin is also measured. Thus, one can arrange his experiment in such a way that he can predict the value of the x component of spin of particle 2, presumably without in any way disturbing it. According to the criterion, the x component of spin of particle 2 is an element of reality. Likewise, one can also arrange his experiment so that he can predict any other component of the spin of particle 2 without disturbing it. The conclusion would be that the x, y, z components of the spin of each particle are the elements of physical reality and must exist without considering which component is being measured. Of course, this is not the viewpoint of quantum mechanics.

The first experiment to realize Bohm's gedanken experiment was a measurement of the polarization correlation between a pair of high-energy photons produced by spin-zero positronium annihilation.[3,4] Since the time

when Bell[5] showed that a local, deterministic, hidden-variable theory has different predictions from those of quantum mechanics in some special experimental situations, a number of experiments have been performed to test his inequalities.[6,7] One type of investigation has been the measurement of the polarization correlation of the visible photon pair emitted in certain atomic radiative cascades.

Our previous experience[8,9] in measuring the absolute quantum efficiencies of photodetectors with simultaneously produced pairs of light quanta with nonlinear optical parametric down conversion has led us to experiment with various methods of forming a two-quantum superposition state of the Einstein-Podolsky-Rosen-Bohm type with such pairs.[10] This has been accomplished by our reflecting the two divergent beams from the nonlinear crystal onto a beam splitter from opposite sides as described in the following paragraph. A new feature of our method is that each of the light quanta is in a definite eigenstate of polarization before the superposition state is formed at the beam splitter. "There seems to be 'nothing hidden' in this approach."[11] If one considers only the amplitude for the two quanta "traveling away" from each other, which can be done experimentally by recording coincidences at the two separated detectors, the state is just the photon polarization version of Bohm's gedanken quantum state.

The experimental arrangement is shown in Fig. 1. For the purpose of clear spacelike separation detection of the two detectors (separated by 50 cm), a 100-ps pulsed laser was chosen. A 3-cm wave packet of the fourth harmonic (wavelength 266 nm) from a Nd-doped yttrium aluminum garnet laser was sent to a 25-mm-long deuterated potassium dihydrogen phosphate nonlinear optical crystal to produce the correlated photon pairs. In nonlinear optical parametric down conversion the phase-matching conditions have to be satisfied:

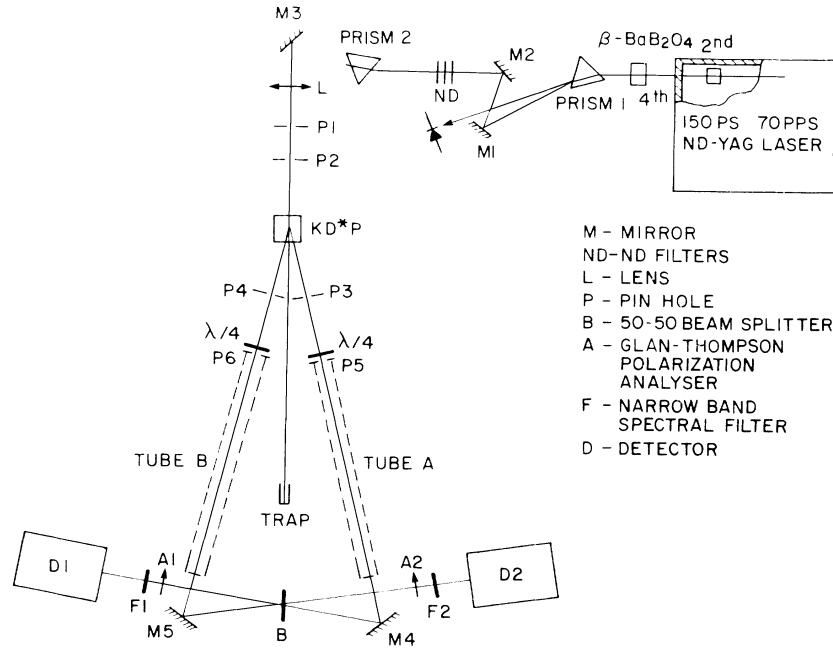$$\omega = \omega_1 + \omega_2, \quad \mathbf{K} = \mathbf{K}_1 + \mathbf{K}_2, \tag{1}$$

FIG. 1. Schematic diagram of the experiment.

where ω and $\mathbf{K}$ are the frequency and the wave vector of the incident beam, and ω_1, ω_2 and $\mathbf{K}_1$, $\mathbf{K}_2$ are the frequencies and the wave vectors of the generated light quanta. The desired photon pair can be produced by cutting the crystal at the desired phase-matching angle. The crystal used in the experiment was a 90° type I phase-matched deuterated potassium dihydrogen phosphate crystal. An exit cone of 532-nm light was generated by the incident 266-nm wavelength laser beam. The three wave vectors $\mathbf{K}$, $\mathbf{K}_1$, and $\mathbf{K}_2$ must be in the same plane according to Eq. (1); therefore, we use two pinholes P_3 and P_4 to select the correlated pair. Each member of the pair was polarized along the Y direction (out of the plane of the paper). The correlation of the photon pair has been studied by several authors.[12,13] The detectors are avalanche photodiodes operated in the Geiger mode[8,10] with quantum efficiencies measured to be 22% and 17%. Each detector is preceded by two 10-Å filters in tandem with a total transmittance factor of 37%. A high-quality linear analyzer of the Glan-Thompson type was placed in front of each detector assembly. The multilayer beam splitter was specially designed to have 50% transmission and 50% reflection for both the S and P components at near-normal incidence for the 532-nm wavelength.

Two different types of polarization eigenstate were

produced by this correlated photon pair. The circular-polarization configuration was obtained by our inserting a $\frac{1}{4}\lambda$ wave plate into the paths A and B to transform the $|Y\rangle$ polarization state to the circular-polarization state $|L\rangle$. These left-hand circular-polarized photons, when reflected from front surface aluminum mirrors M_4 and M_5, change their $|L\rangle$ state to the right-hand circular-polarization state $|R\rangle$. The quantum state of the pair may be written as,

$$|\Phi\rangle = e^{i\alpha}|R^A\rangle \otimes e^{i\beta}|R^B\rangle, \tag{2}$$

where α, β are the phases associated with the paths A and B, respectively. The photons are superposed when they meet at the beam splitter. Each of the right-hand polarized photons from path A and path B has a 50-50 chance to pass through or to be reflected. The polarization state produced by the beam splitter is thus

$$|\Psi\rangle = \frac{1}{2}e^{i\alpha}[|R_1\rangle - |L_2\rangle]e^{i\beta}[|R_2\rangle + |L_1\rangle]. \tag{3}$$

The "natural coordinate system" (right-hand system with the $\mathbf{K}$ direction as the Z axis) is employed here. The reason for the different signs in the brackets is that there is a π phase shift when the reflection is taken from the low to the high index, and no phase shift for the opposite sequence. The final quantum state of this circular-polarization configuration is thus

$$|\Psi\rangle = \frac{1}{2}e^{i(\alpha+\beta)}[|R_1\rangle \otimes |R_2\rangle - |L_1\rangle \otimes |L_2\rangle] + \frac{1}{2}e^{i(\alpha_1+\beta_1)}|R_1\rangle \otimes |L_1\rangle - \frac{1}{2}e^{i(\alpha_2+\beta_2)}|R_2\rangle \otimes |L_2\rangle. \tag{4}$$

A detailed tracing of the optical path shows that $\alpha_1 + \beta_2 = \alpha_2 + \beta_1 \equiv \alpha + \beta$, where α_1 (or β_i) means that photon from path A (or B) to detector i. The four terms correspond to four probability amplitudes: (1) Each of the two photons passes

TABLE I. Correlation measurements for circular-polarization configuration.

θ_1 (deg)	θ_2 (deg)	φ (deg)	N_c/N_1 [a]
0	0	0	0.0018 ± 0.0006
0	90	90	0.0308 ± 0.0025
45	45	90	0.0316 ± 0.0025
45	135	180	0.0030 ± 0.0008

[a] $N_1 = 5000$ for each run.

TABLE II. Correlation measurements for linear-polarization configuration.

θ_1 (deg)	θ_2 (deg)	φ (deg)	N_c/N_1 [a]
0	0	0	0.0016 ± 0.0006
0	90	90	0.0340 ± 0.0026
−30	30	0	0.0010 ± 0.0004
−30	120	90	0.0336 ± 0.0026
−45	45	0	0.0012 ± 0.0005
−45	135	90	0.0326 ± 0.0026
−60	60	0	0.0010 ± 0.0004
−60	150	90	0.0318 ± 0.0025

[a] $N_1 = 5000$ for each run.

through the beam splitter, one to detector 1 and the other to detector 2; (2) each of the two photons is reflected, one to detector 2 and the other to detector 1; (3) photon A passes through the beam splitter and photon B is reflected so that both of them reach detector 1; (4) photon B passes through the beam splitter and photon A is reflected so that both of them reach detector 2.

The second type of polarization state kept a linear-polarization configuration by placing a $\frac{1}{2}\lambda$ wave plate in path A only. Thus the Y-polarized photon in path A would be rotated to X polarization. By our making the same analysis as for the circular configuration, the polarization state is

$$| \Psi \rangle = \frac{1}{2} e^{i(\alpha+\beta)}[\,|X_1\rangle \otimes |Y_2\rangle + |Y_1\rangle \otimes |X_2\rangle\,] + \frac{1}{2} e^{i(\alpha_1+\beta_1)} |X_1\rangle \otimes |Y_1\rangle + \frac{1}{2} e^{i(\alpha_2+\beta_2)} |Y_2\rangle \otimes |X_2\rangle, \tag{5}$$

where again $\alpha_1+\beta_2 = \alpha_2+\beta_1 \equiv \alpha+\beta$. The natural coordinate system is also employed, so that no negative signs appear.

In the experiment, N_c, the coincidence counts for the two detectors, and N_1, the number of counts of the channel-1 detector, were recorded. The ratio N_c/N_1 is then predicted to be[14]

$$N_c/N_1 = \frac{1}{2}\eta_2\epsilon_2\sin^2(\theta_1+\theta_2) = \frac{1}{2}\eta_2\epsilon_2\sin^2(\varphi), \tag{6}$$

for both the circular- and the linear-polarization configurations, where η_2 is the total detection efficiency including the transmittance factors of the narrow-band spectral filters and the quantum efficiency of detector 2, ϵ_2 is the transmittance factor of the analyser 2, θ is the angle between the analyser axis and the X direction and $\varphi = \theta_1 + \theta_2$ is the angle between the axes of the two analysers.

Table I exhibits the measured ratio N_c/N_1 for four different combinations of analyser axis settings, two with the axes perpendicular and two with the axes parallel, for the case of initial eigenstates of circular polarization. Table II displays the measured ratio N_c/N_1 for eight different combinations of analyser axis settings, four with the axes parallel and four with the axes perpendicular, for the case of initial eigenstates of linear polarization. The tables show the expected maximum values when the analyser axes are perpendicular and the expected minimum values when they are parallel. We have also measured N_c/N_1 in the linear-initial-polarization-state case for some intermediate settings of the relative analyzer axis angles as shown in Table III. The comparison with the tabulated values of $\sin^2\varphi$ agrees with Eq. (6) within the experimental error.

We also performed an explicit test of one of Bell's inequalities[6]:

$$\delta = \left| \frac{R_c(3\pi/8)}{R_0} - \frac{R_c(\pi/8)}{R_0} \right| \le \frac{1}{4}, \tag{7}$$

where $R_c(\varphi)$ is the coincidence rate for analyser combination φ and R_0 is the coincidence rate for no analysers. Our experimental value with limited data for Bell's quantity in expression (7) is

$$\delta = 0.34 \pm 0.03, \tag{8}$$

violating the inequality in expression (7) by 3 standard deviations. The experimental results are in good agreement with the quantum-mechanical prediction $\frac{1}{4}\sqrt{2} \cong 0.35$.

This new method of producing a correlated pair of

TABLE III. Comparison of measured correlation with the expected $\sin^2\varphi$ relation.

φ (deg)	N_c/N_1 [a]	Normalized N_c/N_1	$\sin^2\varphi$
22.5	0.0058 ± 0.0011	0.17 ± 0.03	0.15
45.0	0.0178 ± 0.0019	0.53 ± 0.06	0.50
67.5	0.0296 ± 0.0024	0.88 ± 0.07	0.85
90.0	0.0340 ± 0.0026	1.01 ± 0.08	1.00
112.5	0.0304 ± 0.0025	0.90 ± 0.07	0.85
135.0	0.0186 ± 0.0019	0.55 ± 0.06	0.50
157.5	0.0054 ± 0.0010	0.16 ± 0.03	0.15

[a] $N_1 = 5000$ for each run.

photons at definite time and definite **K** vectors will allow a true random delayed-choice EPR experiment to be performed.[15,16] The random delayed-choice idea is difficult to perform in the atomic-cascade emission photon source, because of the necessity of large solid angle of collection and the unknown time of emission of the photon pair.

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

[2]D. Bohm, *Quantum Theory* (Prentice Hall, Englewood Cliffs, NJ, 1951).

[3]C. S. Wu and I. Shaknov, Phys. Rev. **77**, 136 (1950).

[4]L. R. Kasday, J. D. Ullman, and C. S. Wu, Bull. Am. Phys. Soc. **15**, 568 (1970).

[5]J. S. Bell, Physics (Long Island City, N.Y.) **1**, 195 (1964).

[6]For a review, see J. F. Clauser and A. Shimony, Rep. Prog. Phys. **41**, 1881 (1976).

[7]A. Aspect, P. Grangier, and G. Roger, Phys. Rev. Lett. **47**, 460 (1981); A. Aspect, D. Grangier, and G. Roger, Phys. Rev. Lett. **49**, 91 (1982); A. Aspect, J. Dalibard, and G. Roger, Phys. Rev. Lett. **49**, 1804 (1982).

[8]S. R. Bowman, Y. H. Shih, and C. O. Alley, in *Laser Radar Technology and Applications,* edited by J. M. Cruickshank and R. C. Harney, SPIE Conference Proceedings No. 663 (The International Society for Optical Engineering, Bellingham, WA, 1986), p. 24.

[9]D. N. Klyshko, Kvantovaya Elektron. (Moscow) 7, 1932 (1980) [Sov. J. Quantum Electron. **10**, 1112 (1980)].

[10]Y. H. Shih, Ph.D. dissertation, University of Maryland, 1987 (unpublished).

[11]John Wheeler, private communication.

[12]B. Ya. Zel'dovich and D. N. Klyshko, Pis'ma Zh. Eksp. Teor. Fiz. **9**, 290 (1969) [JETP Lett. **9**, 169 (1969)].

[13]S. Friberg, C. K. Hong, and L. Mandel, Phys. Rev. Lett. **54**, 2011 (1985).

[14]For detail see Ref. 10 and C. O. Alley and Y. H. Shih, in *Proceedings of the Second International Symposium on Foundations of Quantum Mechanics in the Light of New Technology,* edited by M. Namiki *et al.* (Physical Society of Japan, Tokyo, 1986), p. 47.

[15]D. Bohm and Y. Aharonov, Phys. Rev. **108**, 1070 (1957).

[16]W. Miller and J. A. Wheeler, in *Proceedings of the International Symposium on Foundations of Quantum Mechanics in the Light of New Technology,* edited by S. Kamefuchi *et al.* (Physical Society of Japan, Tokyo, 1984), p. 140; C. O. Alley, O. Jakubowicz, C. A. Steggerda, and W. C. Wickes, *ibid.,* p. 158; C. O. Alley, O. Jakubowicz, and E. C. Wickes, in *Proceedings of the Second International Symposium on Foundations of Quantum Mechanics in the Light of New Technology,* edited by M. Namiki *et al.* (Physical Society of Japan, Tokyo, 1986), p. 36.