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A New Type of EPR Experiment Using Light Quanta Produced by A Nonlinear Optical Process

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Abstract

A pair of correlated light quanta of 532 nm wavelength with the same linear polarization but divergent directions of propagation was produced by non-linear optical parametric down conversion in a crystal of deuterated potassium di-hydrogen phosphate from a 100 ps duration laser pulse of 266 nm wavelength. Each light quantum was converted to a circular polarization state or a linear polarization state (orthogonal) and was reflected by a turning mirror to superpose with the other at a beam splitter to produce a two-quantum superposition state. For coincident detection of the two light quanta at separated detectors, correlations of the Einstein-Podolsky-Rosen type for the polarizations have been observed as predicted by our analysis. In preliminary runs with limited bata we have measured a violation of Bell's inequality by three standard deviations. We are planning to extend our experiments to include a truly random delayed choice between two analyser settings at each detector while maintaining a spacelike separation between the detectors.

§1. Introduction

Einstein, Podosky and Rosen in their 1935 paper[1] proposed a gedanken experiment to argue that quantum mechanics is incomplete. The EPR gedanken experiment was based on the argument that the non-commuting observables can have simultaneous reality in a gedanken quantum system.EPR first gave their criterion: if, without in any way disturbing the system, we can predicu 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 gedankan experiment was modified by Bohm in 1951[2]. A singlet state of 2 spin

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$\frac{1}{2}$ particles 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 $|\hat{n}_i^\pm>$quantum mechanically describe a state in which particle 1 or 2 has spin "up" or "down" respectively along the direction $\hat{n}$. Suppose one set up his experiment to measure the spin of the 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 with it. The conclusion would be all 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 "*Gedankenexperiment*" was a measurement of the polarization correlation between a pair of high energy photons produced by the spin zero positronium annihilation[3,4]. Since 1964, when Bell[5] showed that a local deterministic hidden variable theory has different predictions from those of quantum mechanics in some special experimental situations, several experiments have been performed to test his inequalities[6~10].

One type if investigation has been the measurement of the polarization correlation of the visible photon pair emitted in certain atomic radiative cascades. In a series of experiments Aspect and his colleagues used a tunable dye laser and a Krypton laser to illuminate an atomic beam of calcium, exciting by two-photon absorption the $4p^2$ $^1S_0$-$4s4p$ $^1P_1$-$4s^2$ $^1S_0$ cascade to produce a pair of correlated photons. This pair was used to test Bell's inequality in different versions. Their experimental results are in excellent agreement with quantum mechanics predictions and strongly against the local deterministic hidden variable theory with high statistical accuracy.

In their 1982 experiment[9] two acousto-optical switches driven by separate 25 MHz oscillators were employed to switch each of the photons between two different analysers at the 50 MHz rate of the zero crossings. Theis was the first and only experiment so far to implement the idea of Bohm and Aharonov: "the settings are changed during the flight of the particles"[11] in the context of testing Bell's inequalities. As pointed out by Aspect et al "the ideal scheme has not been completed since the change is not truly random"[99]. The random delayed choice idea[12] is difficult to perform in the atomic cascade emission photon source, because of the unknown time of emission of the photon pair. Also it is not clear that any eigenstate of polarization has been generated from the atomic cascade emission, the "hidden variable" theory is allowed in the first place.

Our previous experience[13] in measuring the absolute quantum efficiencies of photodectors with simultaneously produced pairs of 532 nm wavelength light quanta by the method of Klyshko[14] using non-linear optical parametric down conversion has led us to experiment with various methods of forming a two-quantum superposition state of the Einstein-Podolsky-Rosen type with such pairs. This has been accomplished by reflecting the two divergent beams from the non-linear crystal onto a beam-splitter from opposite sides as described in the following section.

A new feature of our method is that each of the light quanta is in definite eigenstate of polarization before the superposition state is formed at the beamsplitter. The "hidden variable" theory is not allowed in the first place. 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 that encountered in the other EPR experiments.

The use of 100 ps laser pulses which occur at precisely known times will allow us to implement a delayed random choice as was done in our earlier delayed choice experiments with single light quanta[15]. This will be discussed briefly in § 6.

§2. Description of the Experimental Equipment

The experimental arrangement is shown in Fig. 1. A 100 ps pulse of the fourth harmonic (wavelength 266 nm) from a ND: YAG laser was sent to a 25mm long KD*P nonlinear crystal to produce the correlated photon pairs.

In nonlinear optical parametric down conversion the phase matching condition has to be satisfied:

$$\begin{gathered} \omega = \omega_1 + \omega_2 \\ \boldsymbol{K} = \boldsymbol{K}_1 + \boldsymbol{K}_2 \end{gathered} \tag{1}$$

where ω and $\boldsymbol{K}$ are the frequency and the wavevector of the incident beam, ω_1, ω_2 and $\boldsymbol{K}_1$, $\boldsymbol{K}_2$ are the frequencies and the wavevectors 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 KD*P crystal[16]. A exit cone of 532 nm light was generated by the incident 266 nm wavelength laser beam. The three wavevectors $\boldsymbol{K}$, $\boldsymbol{K}_1$, $\boldsymbol{K}_2$ must be in the same plane according to equation (1), therefore we use two pinholes P_3 and P_4 to select the correlated pair. The time correlation of the photon pair has been studied by several authors[17~19]. The polarizations of the generated photons are determined by the phase matching condition within the KD*P crystal. In this experiment each member of the pair was polarized

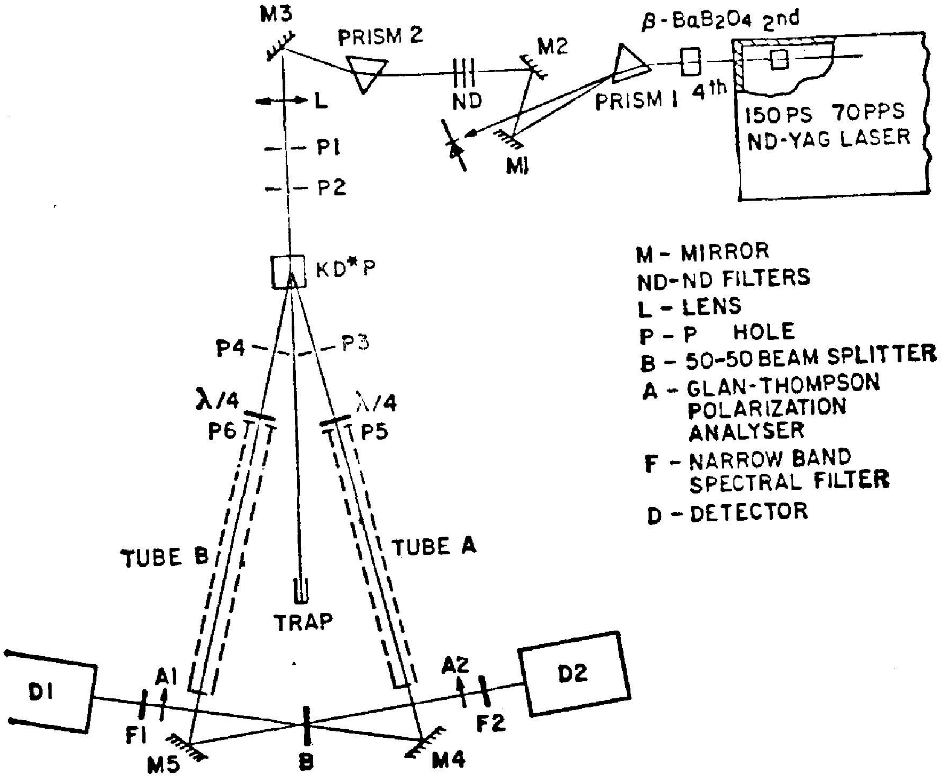

Fig. 1 Schematic diagram of the arrangement of the various components of the experiment

along the Y direction (out of the plane of the paper). The X direction (in the plane of the paper) is defined by the polarization of the incident 266 nm laser beam and the extraordinary ray direction in the crystal.

The detectors are avalanche photodiodes operated in the Geiger mode[13] 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 (transmittance factor of 90%), capable of rotation through an angle of 2π radians, was placed in front of each detector assembly.

The beamsplitter 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.

§3. Polarization State Analysis snd Predictions

Two different types of polarization eigenstates can be produced by this correlated photon pair. The circular polarization configuration is obtained by inserting two $\frac{\lambda}{4}$ waveplates into the paths A and B. A $\frac{\lambda}{4}$ waveplate transforms the $|Y\rangle$ polarization state to the circular polarization state $|L\rangle$ These left hand circular polarized photons when reflected from mirrors M_4 and M_5 change their $|L\rangle$ state to the right hand circular polarization state $|R\rangle$. The quantum stats 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 path A and B respectively. The photons are superposed when they meet at the beamsplitter. 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 beamsplitter 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 $\boldsymbol{K}$ direction as the Z axis) is employed here. The reason for the different signs in the brackets is the different sequences of low→high and high→low indices of refraction encountered by the two photons. There is a π phase shift when the reflection is taken from the low index to the high index and no phase shift for the opposite sequence. The final quantum state of this circular polarization configuration is

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

A detailed tracing of the optical paths shows that

$$\alpha_1 + \beta_2 = \alpha_2 + \beta_1 \equiv \alpha + \beta.$$

The physical meaning of the state is clear. The four terms correspond to four probability amplitudes:.

(1) each of the two photons passes through the beamsplitter 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 beamsplitter and photon B is reflected so that both of them reach detector *1*;

(4) photon B passes through the beamsplitter and photon A is reflected so that both of them reach detector *2*.

The second type of polarization quantum state keeps a linear polarization configuration. Instead of putting $\frac{\lambda}{4}$ waveplates in each of the paths, a $\frac{\lambda}{2}$ waveplate was placed in path A only. Thus the Y polarized photon in path A would be rotated to X polarization. The quantum state may be written as

$$|\Psi\rangle = e^{i\alpha}|X^A\rangle \otimes e^{i\beta}|Y^B\rangle \tag{5}$$

before the beamsplitter. After the beamsplitter, by making the same analysis as for the circular configuration, the quantum state may be considered as

$$\begin{aligned} |\Psi\rangle = {} & \frac{1}{2} e^{i(\alpha+\beta)}[|X_1\rangle \otimes |Y_2\rangle + |Y_1\rangle \otimes |X_2\rangle] \\ & + \frac{1}{2} e^{i(\alpha_1+\beta_1)}|X_1\rangle \otimes |Y_1\rangle \\ & + \frac{1}{2} e^{i(\alpha_2+\beta_2)}|Y_2\rangle \otimes X_2\rangle \end{aligned} \tag{6}$$

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.

The coincidence counts N_c for the two detectors N_c will be,

$$N_c = N\cdot\eta_1\cdot\eta_2\cdot\epsilon_1\cdot\epsilon_2\cdot\langle\Psi|\boldsymbol{Q}_1(\theta_1)\otimes\boldsymbol{Q}_2(\theta_2)|\Psi\rangle \tag{7}$$

where N is the number of photon pairs sent to the detectors, η_1 and η_2 are the detection efficiencies including both the transmittance factors of the narrow band spectral filters and the quantum efficiencies of the detectors. ϵ_1 and ϵ_2 are the transmittance factor of the analysers. $\boldsymbol{Q}_i(\theta_i)$ is the projection operator for linear polarization along an axis in the XY plane and making an angle θ with the X axis,

$$\boldsymbol{Q}_i(\theta_i) = \begin{Bmatrix} \cos^2\theta_i & \cos\theta_i\cdot\sin\theta_i \\ \cos\theta_i\cdot\sin\theta_i & \sin^2\theta_i \end{Bmatrix} \tag{8}$$

To calculate N_c only the first two amplitudes of the $|\Psi\rangle$ in equations (4) and (6) need to be considered. The result is

$$\begin{aligned} N_c &= \frac{1}{4} N\cdot\eta_1\cdot\eta_2\cdot\epsilon_1\cdot\epsilon_2\cdot\sin(\theta_1+\theta_2) \\ &= \frac{1}{4} N\cdot\eta_1\cdot\eta_2\cdot\epsilon_1\cdot\epsilon_2\cdot\sin(\varphi) \end{aligned} \tag{9}$$

for both the circular and the linear polarization configurations, where $\varphi=\theta_1+\theta_2$ is the angle between the axes of the two analysers.

In the actual experiments N_1, the number of counts of the channel 1 detector was recorded as a reference. From equation (9) the ratio N_c/N_1 is then predicted to be

$$\frac{N_c}{N_1} = \frac{1}{2}\eta_2\cdot\epsilon_2\cdot\sin^2(\varphi). \tag{10}$$

§ 4. Experimental Results

In our initial runs the number of registrations N_1 for a given relative setting of the two analyser axis was limited to 5000. This involved about 3×10^6 laser firings which required about 12.5 hours at the 70 Hz rate. We wished to be clearly in the single quantum regime and therefore severely attenuated the intensity of the incident laser pulse before it reached the non-linear crystal.

Table 1 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 2 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. The values are not zero for the latter case. We believe this is caused by the admixture of higher occupation number states in the coherent state associated with the laser pulses used in the experiment. The N_c/N_1 values observed are consistent with the Poisson distribution of such states.

We have also measured N_c/N_1 in the linear initial polarization state case for some intermediate settings of the relative analyser axis angles as shown in Table 3. The comparison with the tabulated values of $\sin^2\varphi$ agrees withf equation (10) within the experimental error when the values of η_2 and ϵ_2 (§ 3) are considered. All the uncertainties given are ± one standard deviation.

Table 1 Correlation Measurements for Circular Polarization Configuration

θ_1°	θ_2°	φ°	N_c/N_1
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

Table 2 Correlation Measurements for Linear Polarization Configuration

θ_1°	θ_2°	φ°	N_c/N_1
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

Table 3 Comparison of Measured Correlation with the Expected $\sin^2\varphi$ Relation

$\varphi°$	N_c/N_1	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

We also used the linear configuation two photon superposition state to perform a preliminary test of Bell's inequality[6]:

$$\delta = \left| R_c(3\pi/8)/R_0 - R_c(\pi/8)/R_0 \right| \leqslant \frac{1}{4} \tag{11}$$

where $R_c(\varphi)$ is the coincidence rate for analyser combination φ and R_0 is the coincidence rate for no analysers. In the actual measurement, N_c and N_0, the time integrals of R_c and R_0 were recorded alternately over 30 minute intervals. With the same attenuation described above, about 25×10^6 laser shots were involved. The final experimental value for $N_c(\varphi)/N_0$ was an average over 50 hours of alternating measurements. The experimental value for Bell's quantity in expression (11) is

$$\delta = 0.34 \pm 0.03 \tag{12}$$

violating the inequality in expression (11) by three standard deviations.

The experimental results are in good agreement with the quantum mechanics predictions, $\sqrt{2}\frac{1}{4} \simeq 0.35$.

§5. Future Experiments

This new method of producing a correlated pair of photons at a predictable time allows a true random delayed choice EPR experiment to be performed. We hope to increase the separation of the detectors from the current distance of 0.5 m to abou 10 m (limited by present laboratory dimensions) and add fast Pockels cell switches and fast random choice devices of the type used in our earlier delayed random choice experiments[15]. To speed up the recording of data, we hope to acquire a suitable laser with a much higher repetition rate. Selected avalanche photodiodes of the kind used here in their Geiger mode for single quantum detection can exhibit quantum efficiencies of 30% or greater. We hope to use such higher efficiency detectors.

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利用由非线性光学过程产生的光量子的新型爱因斯坦-泡道尔斯基-洛森实验

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提　要

利用激光脉冲经过KDP晶体的非线性光学参量过程转换为一对相干光量子。在两个不同探测器上作光子符合探测，观察到爱因斯坦-泡道尔斯基-洛森型偏振相关及对Bell不等式的违背。