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Evidence for phase memory in two-photon down conversion through entanglement with the vacuum

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An experiment has been carried out in which two pairs of light beams produced by down conversion in two nonlinear crystals driven by a common pump were mixed by two beam splitters, and the coincidence rate for simultaneous detections of mixed signal and idler photons was measured. It is found that the down-converted light carries information about the phase of the pump field through the entanglement of the down-converted photons with the vacuum.

INTRODUCTION

Generally a single photon, or a group of photons in a Fock state, carries no information about the phase of the electromagnetic field. Indeed, it has been suggested recently that this property of photons provides a means for distinguishing between classical and nonclassical light in an interference experiment.[1] On the other hand, if the quantum state is a linear superposition of a Fock state with the vacuum, then the light carries phase information. For example, when a coherent pump field interacts with a nonlinear medium so as to generate photon pairs through the process of down conversion,[2] then the down-converted signal and idler photons can carry phase information about the pump field, because the output state is a linear superposition of two-photon states with the vacuum. Another way of expressing the same thing is to note that the interaction Hamiltonian which describes two-photon down conversion is similar to the usual quadrature squeezing operator for a quantum field.[3-5] It is, of course, well known that squeezed states are sensitive to the phase of the field. Similar conclusions have recently been drawn by Grangier, Potasek, and Yurke.[6] They proposed a homodyne scheme for demonstrating the presence of the phase information by mixing the signal and idler photons with a coherent oscillator field. However, because the local oscillator has to oscillate at the down-converted rather than at the pump frequency, the proposed experiment poses difficulties.

We have recently suggested an alternative scheme for showing that the down-converted photons carry information about the phase of the pump field[7] through the contribution of the vacuum state. It requires no homodyning, but depends on the interference of two down-converted photon pairs from two similar crystals with a common pump. The suggestion is related to recently proposed ideas on "two-particle interferometry,"[8,9] in that it involves the interference of two two-photon probability amplitudes. We now report the results of experiments that demonstrate the extraction of pump phase information from the down-converted photons in coincidence counting measurements.

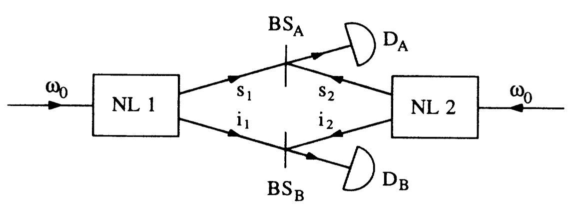

FIG. 1. Principle of the experiment.

THEORY OF THE EXPERIMENT

The principle of the experiment is illustrated in Fig. 1. Two similar nonlinear crystals NL1 and NL2 are optically pumped by identical coherent laser beams at frequency ω_0 derived from a common source. Down-converted signal and idler photons s_1,i_1 and s_2,i_2 emerge from the two crystals in slightly different directions and are mixed by beam splitters BS_A and BS_B, as shown. Mixed signal photons s_1,s_2 then fall on detector D_A and mixed idler photons i_1,i_2 fall on detector D_B. The rate at which D_A and D_B register "simultaneous" detections within some resolving time T_R is measured as the phase difference between the pump beams reaching NL1 and NL2 is varied.

We may taken the state $|\psi\rangle$ of the optical field produced in the two down conversions to be given by the direct product

$$|\psi\rangle = |\psi_1\rangle_1 |\psi_2\rangle_2 , \tag{1}$$

in which each down-converted state $|\psi_j\rangle_j$ $(j=1,2)$ is a linear superposition of the two-photon state $|\omega\rangle_{sj}|\omega'\rangle_{ij}$ with the vacuum state $|\text{vac}\rangle_{sj}|\text{vac}\rangle_{ij}$ $(j=1,2)$. Thus[7]

$$\begin{aligned}|\psi_1\rangle_1 &= M_1|\text{vac}\rangle_{s1}|\text{vac}\rangle_{i1}+\eta_1 F_1 V_1|\omega\rangle_{s1}|\omega'\rangle_{i1} ,\\ |\psi_2\rangle_2 &= M_2|\text{vac}\rangle_{s2}|\text{vac}\rangle_{i2}+\eta_2 F_2 V_2|\omega\rangle_{s2}|\omega'\rangle_{i2} ,\end{aligned} \tag{2}$$

where V_1,V_2 are complex amplitudes representing the coherent pump waves which are treated classically, and η_1,η_2, M_1,M_2, F_1,F_2 are constants with $|\eta_j| \ll 1$. Horne, Shimony, and Zeilinger[8] have referred to such states as "entangled," and it is apparent from Eqs. (2) that the vacuum state provides the bridge for the entanglement. It may be worth noting that, up to $O(\eta)^2$, to which we shall carry the calculation, the state $|\psi\rangle$ is actually not a product state, but a linear superposition of the vacuum with certain two-photon states. If BS_A and BS_B are 50%:50% beam splitters, and if the path lengths from the crystals to the beam splitters are all equal, then the fields at the two detectors are of the form

$$\hat{E}_A^{(+)} \propto (\hat{a}_{s1} + i\hat{a}_{s2}) \,,$$
$$\hat{E}_B^{(+)} \propto (\hat{a}_{i1} + i\hat{a}_{i2}) \,, \tag{3}$$

where $\hat{a}_{s1},\hat{a}_{s2},\hat{a}_{i1},\hat{a}_{i2}$ are photon annihilation operators for the four signal and idler modes. The rate R_{AB} of detecting photons in coincidence at D_A and D_B is then proportional to[10]

$$R_{AB} \propto \langle \psi | \hat{E}_A^{(-)} \hat{E}_B^{(-)} \hat{E}_B^{(+)} \hat{E}_A^{(+)} | \psi \rangle \,, \tag{4}$$

and with the help of Eqs. (1)-(3) it is not difficult to show that when $|\eta_1 F_1 V_1 M_2| = |\eta_2 F_2 V_2 M_1|$, then up to terms of the second order in η_1,η_2 (Ref. 7),

$$R_{AB} \propto |\eta_1 F_1 V_1 M_2|^2 [1 - \cos(\phi_1 - \phi_2 + \arg V_1 - \arg V_2)] \,. \tag{5}$$

ϕ_1,ϕ_2 are the phases of the complex constants $\eta_1 F_1 M_2$ and $\eta_2 F_2 M_1$. It follows from Eq. (5) that the coincidence counting rate R_{AB} carries information about the phases of the pump waves V_1,V_2, and that this phase information depends essentially on the contribution of the vacuum state through the presence of the nonzero constants M_1,M_2 in Eq. (2). If the down-converted photons were in the two-photon Fock state $|\omega'\rangle_s |\omega''\rangle_i$, as is sometimes assumed, no such phase information could be carried.

In practice, the situation is always more complicated, because the down-converted signal and idler photons are not monochromatic but have a large frequency spread. We have shown[7] that a better approximation to the down-converted state is provided by

$$|\psi\rangle = M |\text{vac}\rangle_s |\text{vac}\rangle_i + \eta V \delta\omega \sum_{\omega'} \sum_{\omega''} \phi(\omega',\omega'') \frac{\sin\frac{1}{2}(\omega'+\omega''-\omega_0)t}{\frac{1}{2}(\omega'+\omega''-\omega_0)} \exp[i(\omega'+\omega''-\omega_0)t/2] \, |\omega'\rangle_s |\omega''\rangle_i \,, \tag{6}$$

in which $\delta\omega$ is the mode spacing, for any time t that is large compared with the reciprocal bandwidth, but small compared with the average time interval between down conversions. $\phi(\omega',\omega'')$ is a weight function that is symmetric in ω' and ω'', is peaked at $\omega' = \omega_0/2 = \omega''$, and is normalized so that

$$2\pi \int_0^\infty d\omega \, |\phi(\omega,\omega_0-\omega)|^2 = 1 \,. \tag{7}$$

V is the complex pump field expressed in units such that $|V|^2$ is the rate at which pump photons arrive at the nonlinear crystal, and $|\eta|^2$ is the dimensionless number that gives the ratio of the rate of down-converted photons to the rate of pump photons. If t_A,t_B are the transmissivities of BS_A and BS_B, and α_A,α_B are the quantum efficiencies of detectors D_A and D_B, it may be shown that[7]

$$R_{AB} = 2\alpha_A \alpha_B |t_A t_B \eta_1 V_1 M_2|^2 \times [1 - \cos(\arg V_1 - \arg V_2) + \omega_0(\delta\tau_i + \delta\tau_s)/2] \,, \tag{8}$$

where $\delta\tau_i,\delta\tau_s$ are propagation time differences $\delta\tau_i = \tau_{i1} - \tau_{i2}$, $\delta\tau_s = \tau_{s1} - \tau_{s2}$ between the nonlinear crystals and the respective beam splitters. In the derivation[7] it is assumed that $|\delta\tau_i - \delta\tau_s| \ll 1/\Delta\omega$, and $T_R \gg 1/\Delta\omega$, where $\Delta\omega$ is the effective bandwidth of the signal and idler photons. As before, we find that the two-photon coincidence rate R_{AB} depends on the phases of the two pump waves, because the state of the down-converted light contains a vacuum contribution.

EXPERIMENT

Because of the need for accurate alignment and for keeping optical path differences between the two pump beams constant to a fraction of a wavelength in the course of the experiment, it proved to be more convenient to use the geometry shown in Fig. 2 rather than that of Fig. 1. The UV beam from an argon ion laser operating at 351.1 nm is split into two by the 50%:50% beam splitter BS_0, and two similar pump beams fall on two similar 2.5-cm-long crystals of $LiIO_3$ serving as down converters. Down-converted signal and idler photons at a wavelength of about 700 nm emerge in slightly different directions from both crystals, and they are mixed by the two beam splitters BS_A and BS_B. The optical paths from the crystals to the beam splitters are made as nearly equal as possible. Mixed signal photons and idler photons are then directed to the two thermoelectrically cooled photon counting photomultipliers PMT_A and PMT_B, through 1-mm pinholes and interference filters IF_A and IF_B. Typical photon counting rates were $\sim 10^4$ sec^{-1}, with dark counting rates of about 100 sec^{-1}. The interference filters IF_A and IF_B impose a bandwidth of about 10^{12} Hz on the

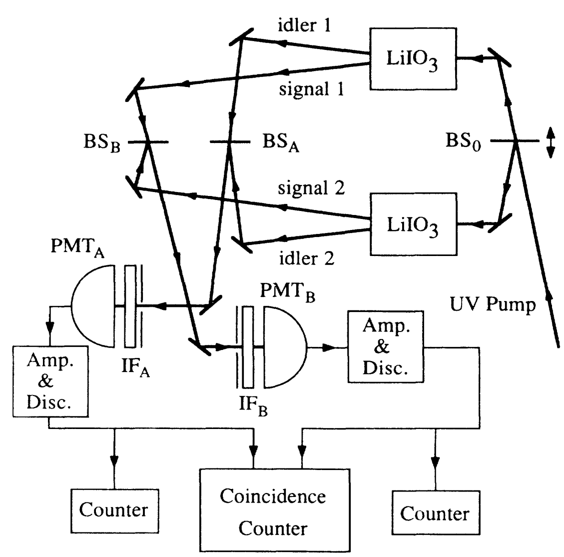

FIG. 2. The setup used in the experiment.

down-converted light, corresponding to a coherence length of about $\frac{1}{3}$ mm. The photoelectric pulses from the two detectors, after amplification and pulse shaping, are counted and sent to a coincidence counter having an effective resolving time of ~ 8 nsec.

With the help of auxiliary He:Ne laser beams the system is first aligned and the path differences $c\delta\tau_s$ and $c\delta\tau_i$ are made equal to better than $\frac{1}{3}$ mm. BS_0 is mounted on a piezoelectric transducer that allows it to be translated in a direction almost perpendicular to its face, as shown in Fig. 2. This causes the phase difference $\arg V_1 - \arg V_2$ to be varied. The object of the experiment is to measure the two-photon coincidence rate after subtraction of accidental coincidences as a function of the displacement of BS_0, and to compare the results with Eqs. (5) or (8). These relations predict that the coincidence rate should vary sinusoidally with optical path difference, and that the visibility of this variation should be 100%. Needless to say, the optical path difference produced by a displacement Δx of BS_0 is actually $2\Delta x$.

Figure 3 shows the results of the experiment. Each data point corresponds to about 1 min of data taking, and the corresponding standard deviation, after subtraction of accidentals, is indicated. It will be seen that the coincidence rate does indeed depend sinusoidally on the phases of the pump beams, with the expected periodicity of $\Delta x = 351.1/2$ nm. However, the observed visibility of the interference pattern never exceeded 40%. The full curve in Fig. 3 is based on Eq. (8) with the phase constant $\omega_0(\delta\tau_i + \delta\tau_s)/2$ adjusted arbitrarily for best fit, but with the cosine multiplied by 0.4.

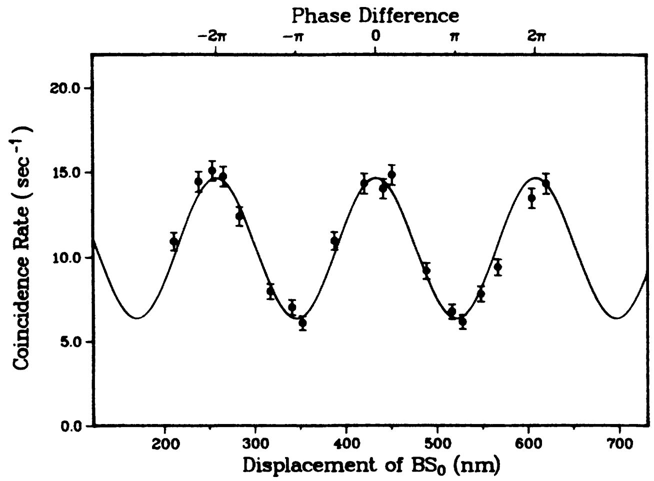

FIG. 3. Observed two-photon coincidence rate as a function of BS_0 displacement. The upper scale shows the phase difference between the two pump waves.

DISCUSSION

Despite the fact that the detector electronics were much slower than the light fluctuations governed by $\Delta\omega$, we have demonstrated that the light produced in the down-conversion process carries information about the pump phase through entanglement with the vacuum. The observed interference effect is based on pairs of photons[11,12] rather than single photons, in the spirit of two-particle interferometry of Horne *et al.*[8] Indeed, it is possible to modify Dirac's famous statement and argue that pairs of photons are interfering with themselves in these experiments. We have not definitely established the reason for the reduction of the observed visibility from 100% to 40%, but we suspect imperfections in the critical alignment of the four down-converted wave fronts, because the visibility is reduced by misalignment. However, the principle that the photons carry information about the pump phase is established, irrespective of the magnitude of the visibility. Finally, the same interference phenomenon could be the basis of a new experimental test for locality violations, in which the measured variables are phase angles rather than polarization angles,[6–9] although violation of the Bell inequality will require larger visibility.

ACKNOWLEDGMENTS

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[1] C. K. Hong, Z. Y. Ou, and L. Mandel, Phys. Rev. A **37**, 3006 (1988).
[2] D. C. Burnham and D. L. Weinberg, Phys. Rev. Lett. **25**, 84 (1970).
[3] H. P. Yuen, Phys. Rev. A **13**, 2226 (1976).
[4] C. M. Caves, Phys. Rev. D **23**, 1693 (1981).
[5] C. M. Caves and B. Schumaker, Phys. Rev. A **81**, 3068 (1985).
[6] P. Grangier, M. T. Potasek, and B. Yurke, Phys. Rev. A **38**, 3132 (1988).
[7] Z. Y. Ou, L. J. Wang, and L. Mandel, Phys. Rev. A **40**, 1428 (1989).
[8] M. A. Horne, A. Shimony, and A. Zeilinger, Phys. Rev. Lett. **62**, 2209 (1989).
[9] B. J. Oliver and C. R. Stroud, Phys. Lett. A **135**, 407 (1989).
[10] R. J. Glauber, Phys. Rev. **130**, 2529 (1963); **131**, 2766 (1963).
[11] R. Ghosh and L. Mandel, Phys. Rev. Lett. **59**, 1903 (1987).
[12] Z. Y. Ou and L. Mandel, Phys. Rev. Lett. **62**, 2941 (1989). For a preliminary account of this work see the *Proceedings of the Sixth Rochester Conference on Coherence and Quantum Optics, June 1989,* edited by J. H. Eberly, L. Mandel, and E. Wolf (Plenum, New York, to be published).