Observation of Nonlocal Interference in Separated Photon Channels

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A two-photon coincidence experiment of the kind recently proposed by J. D. Franson [Phys. Rev. Lett. **62**, 2205 (1989)] has been carried out with signal and idler photons produced in the process of parametric down-conversion. The coincidence rate registered by the two detectors is found to exhibit a cosine variation with the optical path difference, with periodicity equal to the wavelength.

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A number of fourth-order optical interference experiments have been carried out in recent years.[1-8] Unlike conventional second-order interference experiments, these depend on the detection of photon pairs and the interference of two two-photon probability amplitudes.[9] It is an interesting feature of those experiments that quantum mechanics allows the visibility of the interference to be larger for a two-photon state than is allowed by classical electromagnetic theory.

A new and particularly simple form of fourth-order interference experiment with two photons has recently been proposed by Franson[10] as a test for locality violations. The outline of the experiment is shown in Fig. 1. Two photons emitted together by some common source travel along arms A and B to two detectors D_A and D_B, either directly along the shortest path or via a longer path involving reflections from two beam splitters and two mirrors, as shown. Franson supposed that the two photons might be produced by the cascade decay of an atom in which the initial excited state is very long lived. But we may also suppose that the two photons could arise from the down-conversion of a highly monochromatic laser beam, of long coherence time, in a nonlinear crystal.[11] In both cases the two photons are highly correlated in time and their state is an entangled quantum state. Let us suppose that the difference in propagation time between the longer and the shorter paths is the same in both channels and is much greater than the coherence time (reciprocal bandwidth $1/\Delta\omega$) of the light, or the length of each photon wave packet. Then one might naively suppose that there would be no interference. Indeed the mean detection rate registered by D_A or D_B would not show any dependence on path difference. However, we arrive at a different conclusion if we look for simultaneous detections by both D_A and D_B. The two-photon probability amplitude for the shorter paths, A to D_A and B to D_B, then interferes with the two-photon probability amplitude for the longer paths involving the two mirrors. After forming the sum of the two probability amplitudes and squaring we find that the coincidence rate exhibits a cosine variation with a path difference. This is so despite the fact that the two detectors are widely separated and the trajectories of the two photons never mix. We wish to report the results of an experiment in which this nonlocal interference effect, which has no direct classical counterpart, has been observed.

The experiment is shown in Fig. 2. The source of the two photons is the process of spontaneous parametric down-conversion[11] in a crystal of $LiIO_3$ that is optically pumped by the 351.1-nm line of an argon-ion laser. The

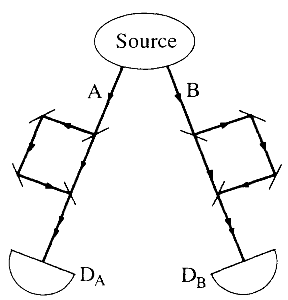

FIG. 1. Outline of the experiment proposed by Franson.

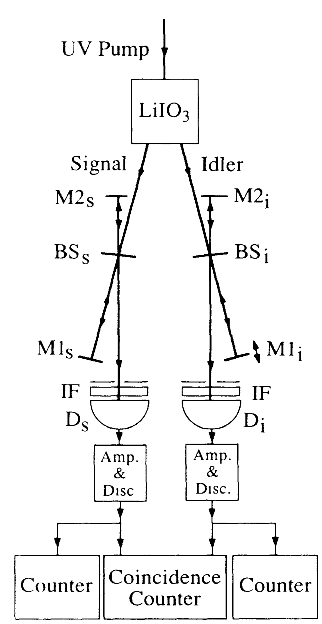

FIG. 2. Outline of the setup for the experiment.

signal (s) and idler (i) photons produced have wavelengths close to 700 nm but substantial bandwidth, which is restricted by interference filters to about 10^{12} Hz. The main difference between the optical arrangement in our experiment and that proposed by Franson is that the variable delay is introduced via an unbalanced Michelson-type interferometer, rather than with the Mach-Zehnder interferometer arrangement shown in Fig. 1. This requires only one beam splitter in each arm instead of two. One of the mirrors $M1_i$ of the Michelson interferometer is mounted on a motor-driven micrometer and can also be moved piezoelectrically, and this allows the optical path difference $2(\mathrm{BS}-M1)_k - 2(\mathrm{BS}-M2)_k \equiv cT_k$ (where $k=s,i$) to be nearly equalized in the two arms, and for T_i to be varied in submicron steps in a controlled manner about the fixed value $cT_i \approx cT_s \approx 3$ cm. The time difference $T_s, T_i \sim 10^{-10}$ sec therefore greatly exceeds the coherence time $1/\Delta\omega \sim 10^{-12}$ sec of the light. In order to make T_s and T_i equal to within 10^{-12} sec in the signal and idler arms, we slowly sweep mirror $M1_i$ through about 5 mm with the help of the micrometer until maximum interference effects show up. The photoelectric pulses from the two detectors, after amplification and pulse shaping, are fed to counters and to a coincidence counter that registers simultaneous detections within the resolving time $T_R \sim 8\times 10^{-9}$ sec.

The results of the measurements, after accidental coincidences are subtracted, are presented in Fig. 3. It will be seen that the two-photon coincidence rate exhibits a cosine variation with small changes of the optical path difference, as expected from the foregoing qualitative argument.

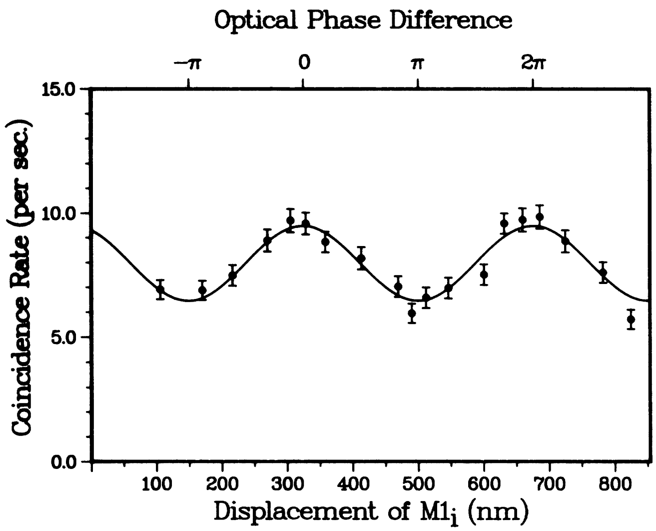

FIG. 3. Observed variation of the two-photon coincidence rate as a function of optical path difference or phase shift ϕ_s. The solid curve is based on Eq. (11) with the constants $\alpha_s\alpha_i|V|^2|\mathcal{R}\mathcal{T}|^4/4$ and $\phi_s+\omega_0 T$ adjusted arbitrarily for the best fit with the data, but with the visibility multiplied by $|\gamma_P(T)|=0.36$.

We now examine the theory of the process quantitatively. We shall analyze the experiment by using the formalism developed in Ref. 12. The fields at the two detectors are represented by the Fourier expansions

$$\hat{E}_s^{(+)}(t) = \left(\frac{\delta\omega}{2\pi}\right)^{1/2} \mathcal{R}\mathcal{T}\sum_{\omega} \hat{a}_s(\omega)(e^{i\omega\tau_{s1}}+e^{i\omega\tau_{s2}})e^{-i\omega t}, \tag{1}$$

$$\hat{E}_i^{(+)}(t) = \left(\frac{\delta\omega}{2\pi}\right)^{1/2} \mathcal{R}\mathcal{T}\sum_{\omega} \hat{a}_i(\omega)(e^{i\omega\tau_{i1}}+e^{i\omega\tau_{i2}})e^{-i\omega t}. \tag{2}$$

Here $\hat{a}_s(\omega)$ and $\hat{a}_i(\omega)$ are photon annihilation operators for the signal and idler modes of frequency ω, which are assumed to be distinct and nonoverlapping. τ_{s1},τ_{i1} are the propagation times of signal and idler photons from beam splitter to detector via mirrors $M1$, whereas τ_{s2},τ_{i2} are the corresponding propagation times via mirrors $M2$. $\delta\omega$ is the mode spacing which is later allowed to tend to zero, and $\mathcal{R},\mathcal{T}$ are the complex reflectivity and transmissivity of the beam splitters. The state $|\psi(t)\rangle$ of the down-converted field at time t after the pump beam is turned on is given by[12]

$$|\psi(t)\rangle = |\mathrm{vac}\rangle_s|\mathrm{vac}\rangle_i + \eta V\delta\omega\sum_{\omega'}\sum_{\omega''}\phi(\omega',\omega'')\frac{\sin\frac{1}{2}(\omega'+\omega''-\omega_0)t}{\frac{1}{2}(\omega'+\omega''-\omega_0)} e^{i(\omega'+\omega''-\omega_0)t/2}|\omega'\rangle_s|\omega''\rangle_i\,, \tag{3}$$

where the sum is to be taken over all signal frequencies ω' and idler frequencies ω'', with fixed pump frequency ω_0. It is assumed in Eq. (3) that t is short compared with the average time between down-conversions. $\phi(\omega',\omega'')$ is a spectral weight function that determines the frequency width of the down-converted light, which satisfies

$$2\pi\delta\omega\sum_{\omega}|\phi(\omega,\omega_0-\omega)|^2=1\,. \tag{4}$$

V is the complex classical pump field in units such that the pump intensity $|V|^2$ is in photons/sec, and $|\eta|^2$ is the fraction of pump photons that is down-converted.

The joint probability of detecting a signal photon with D_s at time t within Δt and an idler photon with D_i at time $t+\tau$

within $\Delta\tau$ is then given by

$$\mathcal{P}_{si}(\tau)=\alpha_s\alpha_i\langle\psi(t)\,|\,\hat{E}_s^{(-)}(t)\hat{E}_i^{(-)}(t+\tau)\hat{E}_i^{(+)}(t+\tau)\hat{E}_s^{(+)}(t)\,|\,\psi(t)\rangle\Delta t\Delta\tau\,, \tag{5}$$

where α_s,α_i are detector quantum efficiencies. If we put

$$\tau_{s2}-\tau_{s1}\equiv T+x_s\,,\quad \tau_{i2}-\tau_{i1}\equiv T+x_i\,, \tag{6}$$

where T is of order 10^{-10} sec and $T\gg 1/\Delta\omega$, whereas $x_s,x_i\ll 1/\Delta\omega$, we then obtain in the limit of long t with the help of Eqs. (1)-(6)

$$\mathcal{P}_{si}(\tau)=\alpha_s\alpha_i\tfrac{1}{8}\,|\eta V|^2|\mathcal{R}\mathcal{T}|^4\Delta t\Delta\tau[\,|\gamma(\tau+\tau_{i1}-\tau_{s1})|^2+\tfrac{1}{2}\,|\gamma(\tau+\tau_{i2}-\tau_{s1}+T)|^2$$
$$+\tfrac{1}{2}\,|\gamma(\tau+\tau_{i1}-\tau_{s1}-T)|^2+|\gamma(\tau+\tau_{i1}-\tau_{s1})|^2\cos(\phi_s+\phi_i+\omega_0T)]\,. \tag{7}$$

Here,

$$\phi_s\equiv\omega_1x_s\,,\quad \phi_i\equiv(\omega_0-\omega_1)x_i \tag{8}$$

are phase shifts associated with the time difference x_s at the middle signal frequency ω_1 and with the time difference x_i at the middle idler frequency $\omega_0-\omega_1$. $\gamma(\tau)$ is the Fourier transform of the weight function $\phi(\omega,\omega_0-\omega)$,

$$\gamma(\tau)=\int\phi(\omega,\omega_0-\omega)e^{-i\omega\tau}d\omega\,, \tag{9}$$

and we have made use of the fact that for very small $x_i,x_s\ll 1/\Delta\omega$,

$$\gamma(\tau+x_s+x_i)\approx\gamma(\tau)e^{-i\omega_1(x_s+x_i)}\,. \tag{10}$$

The measured photon coincidence rate R_{si} is obtained by dividing $\mathcal{P}_{si}(\tau)$ by Δt and integrating with respect to τ over the resolving time T_R. If $T_R\gg T\gg 1/\Delta\omega$ as in our experiment, we are effectively integrating from $\tau=-\infty$ to $\tau=\infty$, and we obtain

$$R_{si}=\alpha_s\alpha_i\tfrac{1}{4}\,|\eta V|^2|\mathcal{R}\mathcal{T}|^4[1+\tfrac{1}{2}\cos(\phi_s+\phi_i+\omega_0T)]\,. \tag{11}$$

In deriving this result we have made use of the relation

$$\int_{-\infty}^{\infty}|\gamma(\tau)|^2d\tau=1\,, \tag{12}$$

that follows from Eq. (4). We therefore expect R_{si} to exhibit a cosine modulation with ϕ_s or ϕ_i of visibility 50%. If we were able to make $T\gg T_R\gg 1/\Delta\omega$, the visibility would be 100%.

Finally, we point out that if the pump beam is not monochromatic of frequency ω_0, but has some second-order normalized two-time autocorrelation function $\gamma_P(\tau)$, then the expected visibility $\mathcal{V}$ is reduced by the factor $|\gamma_P(T)|$, so that

$$\mathcal{V}=\tfrac{1}{2}\,|\gamma_P(T)|\,. \tag{13}$$

It is not difficult to show that for a pump laser with N equally spaced and similar modes covering a total bandwidth $\Delta\omega$,

$$|\gamma_P(T)|=\frac{\sin\frac{1}{2}\Delta\omega T}{N\sin(\frac{1}{2}\Delta\omega T/N)}\approx\frac{\sin\frac{1}{2}\Delta\omega T}{\frac{1}{2}\Delta\omega T}\,, \tag{14}$$

which is independent of N to a first approximation. Now the argon-ion pump laser used in our experiments was operated in a single-line, multimode configuration, in which the number of excited modes fluctuated. Direct measurements of the bandwidth gave values in the range 5-7 GHz,[13] and when these are combined with $T\approx 10^{-10}$ sec in Eq. (14), they yield factors $|\gamma_P(T)|$ in the range 0.64-0.36.

The solid curve in Fig. 3 is based on Eq. (11), but with the visibility $\mathcal{V}$ given by Eq. (13) with $|\gamma_P(T)|=0.36$, which gives best agreement with the data, and with the constant $\alpha_s\alpha_i\frac{1}{4}\,|\eta V|^2|\mathcal{R}\mathcal{T}|^4$ and the constant phase $(\phi_s+\omega_0T)$ adjusted arbitrarily for the best fit. It will be seen that the predicted cosine variation with x_i of period $2\pi/(\omega_0-\omega_1)$ is confirmed. The theoretically expected visibility is fairly sensitive to the value of $\Delta\omega T$, but the model leading to Eq. (14) is of course oversimplified.

In order to understand why Eq. (11) leads to interference with 50% visibility, let us first suppose that the coincidence resolving time T_R is so short that $T_R\ll T$. Then a coincidence detection can occur when both photons follow the short paths through the interferometer, or alternatively when both follow the long paths. Because the detector is unable to distinguish between these two possibilities, the corresponding probability amplitudes add, and interference occurs with unit visibility when the sum is squared to yield the detection probability. On the other hand, when $T_R\gg T$ there are two additional possibilities for a coincidence, for which the probability amplitudes need to be added. These correspond to the signal photon taking the short path while the idler photon takes the long path, and vice versa. The effect of the additional terms is to halve the visibility, leading to the result in Eq. (11).

Some nonlocal features of the interference are especially striking in this experiment. The observed dependence on $\cos(\phi_s+\phi_i)$ implies that the outcome of a measurement, made with the idler detector D_i at the same time as detector D_s registers a photon, depends on the path difference x_s in the signal channel. Yet the two detectors and interferometers may be far apart, and the light in the signal and idler channels is never mixed.

There remains the question whether two classical light waves $V_s(t), V_i(t)$ could account for the observed effects. It is possible to construct a mathematical ensemble of waves that exhibit the same interference, but it is nonergodic and unphysical. For example, if $V_s(t), V_i(t)$ are two strictly monochromatic realizations of the ensemble with frequencies that sum to ω_0, but with every realization corresponding to a different pair of frequencies within the bandwidth $\Delta\omega$, then $\langle |V_s(t)|^2 |V_i(t+\tau)|^2 \rangle$ gives rise to a $\cos(\phi_s + \phi_i)$ interference term. However, when the waves $V_s(t), V_i(t)$ characterizing one realization have Fourier components covering $\Delta\omega$, the interference becomes negligibly small. The nonergodic features of the ensemble seem to be absolutely essential for producing the interference effect, even if ergodic components are added to make some of the correlation times finite.[14] The reason is of course that two classical light waves can give rise to photoelectric coincidence counts repeatedly, whereas one photon pair can produce but one coincidence, and therefore successive photon pairs generate the ensemble automatically. That is why, with the nonergodic classical ensemble described above, the experiment would have to be initiated over and over again, rather than run continuously. To the extent that the experiment was actually performed by accumulating coincidence counts continuously for each ϕ_s, ϕ_i, without disturbing the source or detector in any way, classical electromagnetic wave theory cannot account for the observations.

Because there is no mixing of the emitted photons, the nonclassical and nonlocal features of the interference are possibly more apparent in this experiment than in some of the earlier quantum interference experiments.[1-8] Although experiments to exhibit violations of Bell's inequality would require higher visibility of the interference and call for $T \gg T_R$, we have nevertheless confirmed the principle of two-photon interference under conditions of very great path difference.

After this paper was submitted we learned of a similar experiment that was recently performed by Kwiat *et al.*[15]

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