Interference and indistinguishability governed by time delays in a low-Q cavity

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An interference experiment with signal photons from two parametric down-converters, based on the process of induced coherence without induced emission, has been performed. A low-Q optical cavity provides a possible time delay for the idlers. Whether the idler photon is to be delayed or not then determines whether the signal photon behaves like a wave and exhibits interference or behaves like a particle.

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I. INTRODUCTION

The existence of certain quantum effects in one-photon and two-photon interference experiments is now well established [1–22]. Moreover, experiments with two parametric down-converters [10,15,16,21] have been shown to provide new insight into the interpretation of the quantum state, with emphasis on the fact that a diagonal density operator reflects not only what is known but also what is known in principle. In the following we report on an interference experiment based on the process of induced coherence without induced emission [15,16], but involving an optical cavity. In this experiment the photon appears to "make the decision" whether to behave like a wave and exhibit interference or behave like a particle, while we observe the results.

II. EXPERIMENT

Figure 1 shows an outline of the experimental setup, which is reminiscent of Refs. [15–17]. Two nonlinear crystals, NL1 and NL2, acting as parametric down-converters are optically pumped by mutually coherent pump beams $V_1(t)$, $V_2(t)$ derived from the same laser beam with the help of pump beam splitter BS_p. As a result, down-conversion can occur at NL1 with the emission of simultaneous signal s_1 and idler i_1 photons, or down-conversion can occur at NL2 with the emission of s_2 and i_2 photons. The two crystals are so aligned that the i_1 photon passes through NL2 and lines up with i_2. At the same time, s_1 and s_2 are combined at the movable 50%:50% signal beam splitter BS_s and the combined light falls on the signal detector D_s. Interference between s_1 and s_2 shows up as a cosine variation of the photon-counting rate of D_s when BS_s is translated in the direction shown. It has been demonstrated before that these interference effects disappear, and s_1, s_2 behave as mutually incoherent beams, when the i_1 photon is blocked and prevented from reaching NL2 [15,16]. This can be understood in terms of the potential distinguishability of the paths of the detected signal photon. When a beam splitter BS_i is inserted into the path of i_1 and the emerging light falls on photodetector D_i, the visibility of the interference registered by D_s is reduced. However, when photons are detected by both D_s and D_i in coincidence,

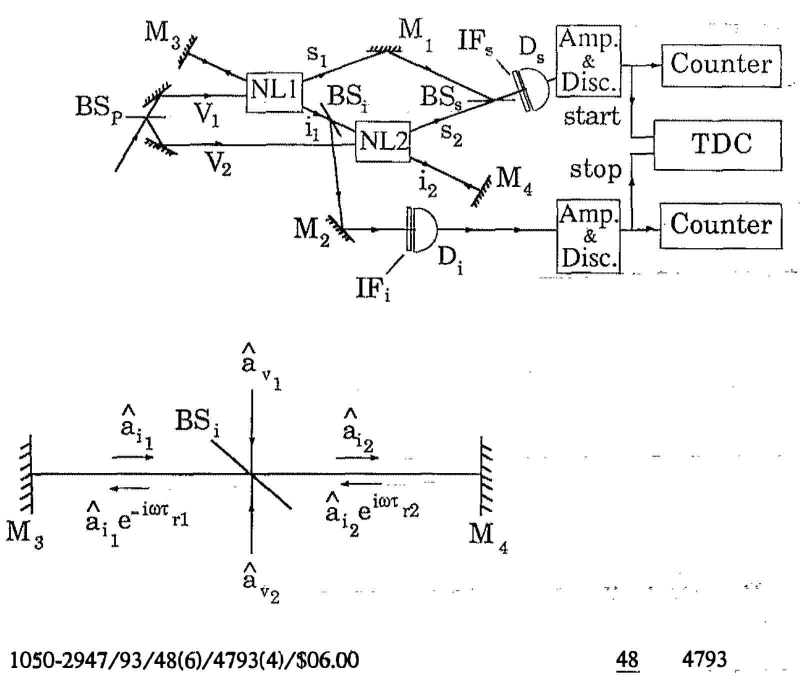

FIG. 1. Outline of the experimental setup. The inset illustrates the definitions of various field amplitudes.

with path length BS_i to $M2$ to D_i equal to path length BS_i to NL2 to D_s, it has been found that the two-photon coincidence rate exhibits no interference as BS_s is translated [17]. This outcome violates certain predictions based on the idea of an empty deBroglie pilot wave, but it is to be expected on the basis of conventional quantum mechanics, because coincidental detections are necessarily due to photons emitted by NL1.

The essential element in the new experiment is that two plane, highly reflecting mirrors M_3 and M_4 are inserted in line with i_1 and i_2, as shown, so as to form a rudimentary low-Q cavity. One might then expect intuitively that simultaneous detections of photons by D_s and D_i would again be associated with emission from NL1, so that again there is no interference. On the other hand, a photon detection by D_i after a detection by D_s, with a time delay corresponding to one or more cavity round trips, makes it impossible to determine where the photons originate.

Let τ_0', τ_0'' be propagation times from NL1 to BS_i and from BS_i to NL2, with $\tau_0'+\tau_0''\equiv\tau_0$. Let τ_1, τ_2 be propagation times of signal photons from NL1 to D_s, and from NL2 to D_s, and let τ_3' be the propagation time of idler photons from BS_i to D_i. We denote twice the propagation time from mirror M_3 to BS_i and from M_4 to BS_i by τ_{r1}, τ_{r2}, so that $\tau_{r1}+\tau_{r2}=\tau_r$, the round trip time for the cavity. Then if a single photon is detected by D_s at time t, it must have been emitted at time $t-\tau_1$ if it comes from NL1, or at time $t-\tau_2$ if it comes from NL2. If the idler photon comes from NL1, after taking one trip around the cavity it will arrive at detector D_i at time $t-\tau_1+\tau_0'+\tau_r+\tau_3'$, or if it comes from NL2 it will arrive at D_i at time $t-\tau_2+\tau_r-\tau_0''+\tau_3'$. But if the interferometer is balanced so that $\tau_0+\tau_2=\tau_1$ then these two times are exactly equal, and it is impossible to tell from the delay between D_s and D_i pulses where the photons originated. Interference is therefore to be expected after one or more round trips, and this is indeed observed.

The measurement is performed by feeding the outputs from detectors D_s and D_i, after amplification and pulse shaping, to counters and to the start and stoop inputs of a time-to-digital converter TDC, and registering the counts as a function of the time delay τ_D between start and stop pulses and for several displacements y of the beam splitter BS_s. We then use a least-squares method to fit the TDC counts for a given delay τ_D to an oscillating function $N(y)$ with given period, and we extract the visibility $\vartheta(\tau_D)$ of the interference pattern.

III. THEORY

Because of the cavity we can no longer treat i_2, i_2 as independent modes of the field. The relevant modes are defined in Fig. 1, in which v_1 and v_2 are vacuum modes. With the help of the inset in Fig. 1 we can express the field amplitudes $a_{i1}(\omega)$, $a_{i2}(\omega)$ in terms of $a_{v1}(\omega)$, $a_{v2}(\omega)$. Let $\mathcal{T},\mathcal{R}$ be the transmissivity and reflectivity of BS_i from the NL1 side and $\mathcal{T}$, $\mathcal{R}'$, from the other side. Then from Fig. 1 one obtains for the Fourier amplitudes in the interaction picture,

$$a_{i1}(\omega)e^{-i\omega\tau_{r1}}=\mathcal{T}'a_{i2}(\omega)e^{i\omega\tau_{r2}}+\mathcal{R}a_{v2}(\omega)e^{i\omega\tau_0'}\,, \tag{1}$$

$$a_{i2}(\omega)=\mathcal{T}a_{i1}(\omega)+\mathcal{R}'a_{v1}(\omega)e^{-i\omega\tau_0'} \tag{2}$$

from which it follows that

$$a_{i1}(\omega)=\frac{\mathcal{T}'\mathcal{R}'a_{v1}(\omega)e^{i\omega(\tau_r-\tau_0')}+\mathcal{R}a_{v2}(\omega)e^{i\omega(\tau_{r1}+\tau_0')}}{1-\mathcal{T}\mathcal{T}'e^{i\omega\tau_r}}\,, \tag{3}$$

$$a_{i2}(\omega)=\frac{\mathcal{R}'a_{v1}(\omega)e^{-i\omega\tau_0'}+\mathcal{T}\mathcal{R}a_{v2}(\omega)e^{i\omega(\tau_{r1}+\tau_0')}}{1-\mathcal{T}\mathcal{T}'e^{i\omega\tau_r}} \tag{4}$$

The electromagnetic fields at detectors D_s and D_i can now be expanded in the form

$$E_s^{(+)}(t)=\left[\frac{\delta\omega}{2\pi}\right]^{1/2}\frac{1}{\sqrt{2}}\sum_{\omega}\left[a_{s1}(\omega)e^{-i\omega(t-\tau_1)}+ia_{s2}(\omega)e^{i\mathbf{k}_s\cdot(\mathbf{r}_2-\mathbf{r}_1)}e^{-i\omega(t-\tau_2)}\right]\,, \tag{5}$$

$$E_i^{(+)}(t)=\left[\frac{\delta\omega}{2\pi}\right]^{1/2}\sum_{\omega}\left[\mathcal{R}a_{i1}(\omega)e^{-i\omega(t-\tau_0'-\tau_3')}+\mathcal{T}'a_{v1}(\omega)e^{-i\omega(t-\tau_3')}\right]\,, \tag{6}$$

in which $\mathbf{r}_1$, $\mathbf{r}_2$ are the positions of the centers of NL1 and NL2 and $\delta\omega$ is the mode spacing. For the quantum state of the field produced by the down-converters at time t in the interaction picture, when the pump is turned on a time $t-t_1$, we have as before [16], because the cavity is of low Q,

$$|\psi(t)\rangle = |\text{vac}\rangle_{s_1 s_2 v_1 v_2} + \left[\frac{\delta\omega}{2\pi}\right]^{3/2} \eta_1 \sum_{\omega_1}\sum_{\omega_1'}\sum_{\omega_1''} \phi_1(\omega_1',\omega_1'';\omega_1) u_1(\omega_1) e^{i(\omega_1'+\omega_1''-\omega_1)(t-t_1/2)} \times \frac{\sin(\omega_1'+\omega_1''-\omega_1)t_1/2}{(\omega_1'+\omega_1''-\omega_1)/2} |\omega_1'\rangle_{s_1} a_{i1}^\dagger(\omega_1'')|\text{vac}\rangle_{s2,v1,v2}$$
$$+ \left[\frac{\delta\omega}{2\pi}\right]^{3/2} \eta_2 \sum_{\omega_2}\sum_{\omega_2'}\sum_{\omega_2''} e^{i(\mathbf{k}_2-\mathbf{k}_2'-\mathbf{k}_2'')(\mathbf{r}_2-\mathbf{r}_1)} \phi_2(\omega_2',\omega_2'';\omega_2) u_2(\omega_2) e^{i(\omega_2'+\omega_2''-\omega_2)(t-t_1/2)} \times \frac{\sin(\omega_2'+\omega_2''-\omega_2)t_1/2}{(\omega_2'+\omega_2''-\omega_2)/2} |\omega_2'\rangle_{s_2} a_{i2}^\dagger(\omega_2'')|\text{vac}\rangle_{s1,v1,v2} . \quad (7)$$

Here, η_1, η_2 are constants representing the down-conversion efficiencies of the two crystals, ϕ_1, ϕ_2 are normalized spectral functions that depend on the phase matching, and $u_1(\omega)$, $u_2(\omega)$ are Fourier amplitudes of the pump beams. The summations are carried out over all signal and idler frequencies. If T_R is the channel width of the TDC, then the rate of counting photons in a channel corresponding to the delay τ_D is given by

$$R(\tau_D) = \alpha_s \alpha_i \int_{\tau_D - T_R/2}^{\tau_D + T_R/2} d\tau \langle \psi(t)|\hat{E}_s^{(-)}(t)\hat{E}_i^{(-)}(t+\tau)\hat{E}_i^{(+)}(t+\tau)\hat{E}_s^{(+)}(t)|\psi(t)\rangle , \quad (9)$$

provided τ_D is much shorter than the average time interval between successive down-conversions. α_s, α_i are the quantum efficiencies of the two detectors. After some nontrivial manipulations and after expanding the denominators in Eqs. (3) and (4) in a Taylor series, Eqs. (3)–(9) lead to the following results according to the value of the delay τ_D:

$$R(\tau_D) = \tfrac{1}{2}\alpha_s\alpha_i |\mathcal{R}|^2 |\eta_1|^2 \langle I_1\rangle \quad \text{if } -T_R/2 \le \tau_D \le T_R/2 ,$$
$$= \tfrac{1}{2}\alpha_s\alpha_i |\mathcal{R}|^2 |\mathcal{T}|^2 [|\eta_1|^2\langle I_1\rangle |\mathcal{T}|^2 + |\eta_2|^2\langle I_2\rangle - \eta_1^*\eta_2\mathcal{T}^*(\langle I_1\rangle\langle I_2\rangle)^{1/2}\gamma_{12}^{(p)}(\tau_1-\tau_2)\gamma(\tau_0+\tau_2-\tau_1)e^{i\omega_i(\tau_0+\tau_2-\tau_1)} + \text{c.c.}] \quad \text{if } \tau_r - T_R/2 \le \tau_D \le \tau_r + T_R/2 ,$$
$$= \tfrac{1}{2}\alpha_s\alpha_i |\mathcal{R}|^2 |\mathcal{T}|^6 [|\eta_1|^2\langle I_1\rangle |\mathcal{T}|^2 + |\eta_2|^2\langle I_2\rangle - \eta_1^*\eta_2\mathcal{T}^*(\langle I_1\rangle\langle I_2\rangle)^{1/2}\gamma_{12}^{(p)}(\tau_1-\tau_2)\gamma(\tau_0+\tau_2-\tau_1)e^{i\omega_i(\tau_0+\tau_2-\tau_1)} + \text{c.c}] \quad \text{if } 2\tau_r - T_R/2 \le \tau_D \le 2\tau_r + T_R/2 , \quad (10)$$

etc.

The solution with τ_D centered on zero time delay gives a constant rate $R(\tau_D)$ without interference, corresponding to idler i_1 photons that are reflected by BS_i and emerge directly from the cavity. The solution in which τ_D is centered on one or more cavity round trip delays τ_r gives a lower counting rate $R(\tau_D)$ and exhibits interference. It corresponds to idlers that have made one or more trips around the cavity before they emerge. At intermediate values of τ_D the rate $R(\tau_D)$ is zero. $\langle I_1\rangle$, $\langle I_2\rangle$ are the light intensities of the pump beams, $\gamma_{12}^{(p)}(\tau)$ is their normalized mutual coherence function, and $\gamma(\tau)$ is the Fourier transform of the spectral density $|\phi(\omega_s-\omega,\omega_i+\omega)|^2$ on the assumption that $\phi_1=\phi_2=\phi$. It follows from Eq. (10) that there is no interference with zero or short time delays between signal and idler, but that interference shows up when the idler photon is delayed by one or more cavity round trips.

Of course the sharp, rectangular form of $R(\tau_D)$ is the result of ignoring the time resolution of the detectors and associated electronics and treating them as infinitely fast. If the detectors actually have a response function $g(\tau)$ (normalized to unity) then Eq. (10) for $R(\tau_D)$ has to be modified so that the first term on the right is multiplied by $g(\tau_D)$, the second term corresponding to one round trip is multiplied by $g(\tau_D-\tau_r)$, the third term corresponding to two round trips is multiplied by $g(\tau_D-2\tau_r)$, etc. In addition a constant A should be added to $R(\tau_D)$ to allow for accidentals in each TDC channel τ_D. $R(\tau_D)$ is then a continuous function of τ_D instead of being discontinuous. As a result, the visibility $\mathcal{V}(\tau_D)$ of the interference pattern given by Eq. (10) after one round trip, say,

$$\mathcal{V}(\tau_D) = \frac{2|\mathcal{T}||\gamma_{12}^{(p)}||\gamma|}{|\mathcal{T}|^2+1} , \quad (11)$$

with $|\eta_1|=|\eta_2|$, $\langle I_1\rangle=\langle I_2\rangle$, has to be replaced by

$$\mathcal{V}'(\tau_D) = \frac{\mathcal{V}(\tau_D)}{1+A/\eta_1\langle I_1\rangle g(\tau_D-\tau_r)} , \quad (12)$$

and similarly after several round trips. This also results in a continuous function of τ_D. In practice, the observed visibility $\mathcal{V}(\tau_D)$ is always smaller than that given by Eq. (11), because the idlers overlap only partially.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The results of the measurements are presented in Fig. 2. Figure 2(a) gives the number of photons counted in

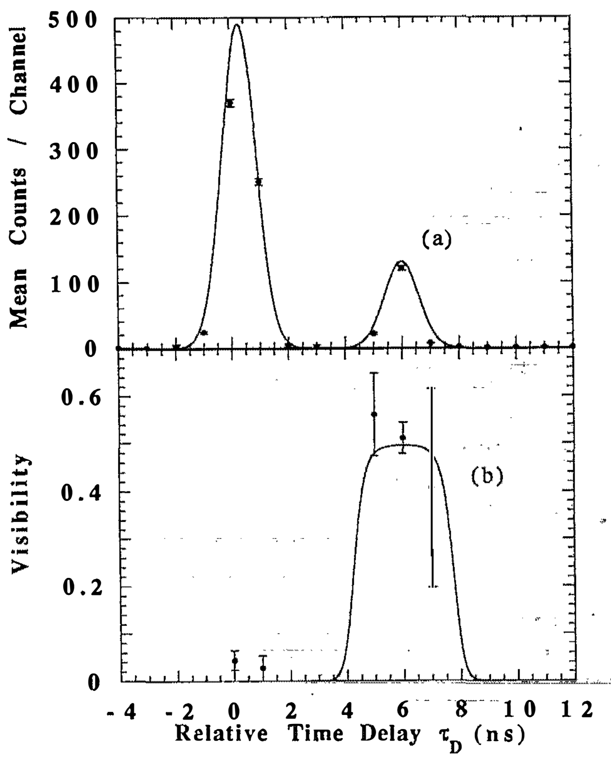

FIG. 2. (a) Measured values of the TDC counts $N(\tau_D)$ in a channel corresponding to the delay τ_D. The standard deviations are comparable with or smaller than the dot size. The full curve is a smooth function fitted to the data. (b) Derived values of the visibility as a function of time delay τ_D, together with their standard deviations. The full curve is based on Eq. (12) with $g(\tau)$ Gaussian of zero mean and standard deviation 0.5 nsec.

channel τ_D of the TDC in a 1-ns interval, which is proportional to $R(\tau_D)$. Typical counting rates of the photodetectors were $R_s \sim 1500$ sec and $R_i \sim 7000$ sec, with $|\mathcal{R}|^2 \approx 1/2 = |\mathcal{T}|^2$. The separation of about 6 nsec between the two peaks in Fig. 2(a) corresponds to the cavity round trip time τ_r. Because of the large cavity losses and the decreasing overlap between i_1 and i_2 with distance, the contribution resulting from two or more round trips are essentially undetectable.

Figure 2(b) gives the measured visibility of the interference as a function of the delay τ_D, together with the standard deviation, obtained by the least-squares procedure described above. Between the two peaks the number of counts (after subtraction of accidentals) is so small as to make it meaningless to extract the visibility. We have not shown data points in which the standard deviation of $\mathcal{V}(\tau_D)$ exceeds $\mathcal{V}(\tau_D)$. Also shown in Fig. 2(b) is the theoretically expected visibility given by Eq. (12) with $A/\eta_1\langle I\rangle g(0) \approx 0.01$, and with $g(\tau)$ of Gaussian form centered on zero with standard deviation 0.5 nsec. Although the statistical uncertainties are relatively large, the absence of interference at zero time delay and the appearance of interference effects after a delay corresponding to one cavity round trip are confirmed.

An interesting feature of the experiment is that the time delay τ_D, which determines whether the signal photons exhibit interference or not, is registered by the stop pulse from detector D_i well after the signal photon has already decided whether to interfere or not. This is reminiscent of earlier delayed choice experiments [2,6]. In some sense, therefore, it is the decision by the idler whether to be transmitted or reflected by beam splitter BS_i which determines whether the conjugate signal light exhibits wavelike or particlelike behavior. This is another manifestation of the entanglement of signal and idler photons.

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