

Induced Coherence and Indistinguishability in Optical Interference

X. Y. Zou, L. J. Wang, and L. Mandel

Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

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Second-order interference is observed in the superposition of signal photons from two coherently pumped parametric down-converters, when the paths of the idler photons are aligned. The interference exhibits certain nonclassical features; it disappears when the idlers are misaligned or separated by a beam stop. The interpretation of this effect is discussed in terms of the intrinsic indistinguishability of the photon paths.

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In recent years a number of optical interference experiments have been reported that exhibit nonclassical and nonlocal features [1-16]. With few exceptions [1,2] most of the observed interference effects were of the fourth order and depended on the use of correlated photon pairs [17]. However, such features can also show up in certain second-order interference experiments in which only one photon is detected, as has been emphasized [18,19]. For example, some so-called "delayed choice" interference experiments are of this type [2,9]. We wish to report a rather striking example of a second-order interference experiment exhibiting nonclassical features, which is counterintuitive in terms of both light waves and photons.

Consider the experimental situation illustrated in Fig. 1, in which two similar nonlinear crystals NL1 and NL2 are optically pumped by two mutually coherent, classical pump waves of complex amplitudes V_1 and V_2 , and parametric down-conversions occur at both crystals, each with the emission of a signal photon and an idler photon. We look for interference between the signal photons s_1, s_2 whose trajectories come together at beam splitter BS_O , when the trajectories of the two idlers i_1, i_2 are aligned, as shown, and the path difference between s_1 and s_2 is varied slightly.

If the intensity of the down-converted i_1 field were very great, one would expect this to induce down-conversions in NL2, such that the i_1 and i_2 fields are mutually

coherent, and then s_1 and s_2 are necessarily mutually coherent also [20]. However, it is found that s_1 and s_2 interfere even if there is no induced emission from NL2 and the down-conversions are spontaneous, even when an i_1 photon from NL1 and an s_2 photon from NL2 never accompany each other. Suppose that photodetector D_s detects signal photons, while photodetector D_i detects idler photons, as shown in Fig. 1. If the alignment is sufficiently good that modes i_1 and i_2 coincide, then it is not difficult to see why the rate R_{si} of two-photon detection by D_s and D_i in coincidence should exhibit fourth-order interference. The reason is that the detectors cannot distinguish between the photon pairs s_1, i_1 and s_2, i_2 , and therefore the corresponding two-photon probability amplitudes add. This interference effect in the coincidence rate R_{si} is indeed observed. But if almost every signal photon from NL1 or NL2 detected by D_s is accompanied by an idler photon falling on D_i , then detector D_i really becomes superfluous, and the counting rate R_s registered by D_s alone also exhibits interference. The phenomenon then becomes a second-order effect. In the absence of complete correlation between the signal and idler photons reaching D_s and D_i , the visibility of the second-order interference would be smaller than the visibility of the fourth-order interference.

Now let us suppose that the connection between i_1 and i_2 is broken, either by insertion of a beam stop between

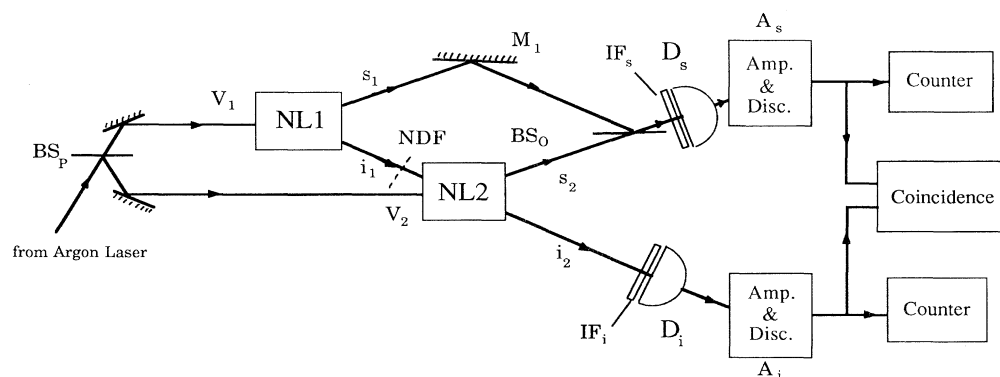


FIG. 1. Outline of the interference experiment.

the two crystals or by misalignment of the two idlers. At first sight it might seem that this should have no effect on the observed second-order interference between the two signals s_1 and s_2 , because the photons are emitted spontaneously, and detector D_s still cannot tell whether the detected photon comes from NL1 or NL2. A moment's thought will show, however, that this is true only so long as i_1 and i_2 are superimposed and aligned. Once the connection or alignment is broken, it is possible in principle to determine from the counts registered by D_i (especially if D_i has close to 100% efficiency) whether the signal photon registered by D_s comes from NL1 or NL2. If both detectors D_s and D_i register, then the photon comes from NL2, and if D_i does not register when D_s does, the photon comes from NL1. This possibility of distinguishing between the two sources wipes out the second-order interference. We have observed this nonclassical interference effect, and the transition between the two extremes.

In order to describe this phenomenon quantitatively, we consider the oversimplified and idealized situation in which each signal and idler field is monochromatic and of frequency ω_s and ω_i , respectively, while the classical pump waves $V_1(t), V_2(t)$ are of frequency $\omega_s + \omega_i$. The parametric interaction \hat{H}_{I_j} at the nonlinear crystal j

($j=1,2$) is of the form

$$\hat{H}_{I_j} = \hbar g_j V_j(t) \hat{a}_{i_j}^\dagger \hat{a}_{s_j}^\dagger + \text{H.c.} \quad (1)$$

in which g is a frequency proportional to the nonlinear susceptibility of the medium and $V_j(t)$ is dimensionless. $\hat{a}_{i_j}, \hat{a}_{s_j}$ are photon annihilation operators for the idler and signal photons emitted from crystal j . If the down-converted modes i_1 and i_2 are perfectly aligned, they may be treated as one mode. In order to allow a continuous transition between the extremes of perfect alignment and misalignment of i_1, i_2 , or between opening the path from NL1 to NL2 and inserting a beam stop between the crystals, we consider an attenuator in the form of a symmetric beam splitter inserted between NL1 and NL2, as shown dashed in Fig. 1. If \hat{a}_0 describes the vacuum field at the unused input port, then the mode amplitudes \hat{a}_{i_2} and \hat{a}_{i_1} are connected by

$$\hat{a}_{i_2} = \mathcal{T} \hat{a}_{i_1} + \mathcal{R} \hat{a}_0, \quad (2)$$

where \mathcal{R} and \mathcal{T} are the complex-amplitude reflectivity and transmissivity of the beam splitter, and $|\mathcal{R}|^2 + |\mathcal{T}|^2 = 1$. On making use of Eq. (2) in Eq. (1), we obtain for the state $|\psi\rangle$ resulting from the interaction in the interaction picture, when the initial state is the vacuum,

$$|\psi\rangle = |\text{vac}\rangle_{s_1, i_1, s_2, 0} + f_1 V_1(t) |1\rangle_{s_1} |1\rangle_{i_1} |0\rangle_{s_2} |0\rangle_0 + f_2 V_2(t + \tau_0) e^{-i\theta_0} (\mathcal{T}^* |0\rangle_{s_1} |1\rangle_{i_1} |1\rangle_{s_2} |0\rangle_0 + \mathcal{R}^* |0\rangle_{s_1} |0\rangle_{i_1} |1\rangle_{s_2} |1\rangle_0). \quad (3)$$

$|f_1|^2, |f_2|^2$ are the fractions of the incident light energy which are down-converted, τ_0 is the propagation time from NL1 to NL2, and we have neglected terms with more than two photons.

We denote by θ_0, θ_1 , and θ_2 the phase shifts associated with the propagation from NL1 to NL2, from NL1 to D_s , and from NL2 to D_s , respectively (see Fig. 1). Then the (dimensionless) field at detector D_s may be written

$$\hat{E}_s^{(+)} = \hat{a}_{s_1} e^{i\theta_1} + \hat{a}_{s_2} e^{i\theta_2}. \quad (4)$$

The average rate of counting of detector D_s is proportional to $R_s = \langle \psi | \hat{E}_s^{(-)} \hat{E}_s^{(+)} | \psi \rangle$, and with the help of Eqs. (3) and (4) this yields

$$R_s = |f_1|^2 \langle I_1 \rangle + |f_2|^2 \langle I_2 \rangle + 2 |f_1 f_2| \langle (I_1 \rangle \langle I_2 \rangle)^{1/2} |\gamma_{12}| |\mathcal{T}| \cos(\theta_0 + \theta_2 - \theta_1 + \arg f_2 - \arg f_1 - \arg \mathcal{T} + \arg \gamma_{12}), \quad (5)$$

where $I_j = |V_j|^2$ ($j=1,2$) and

$$\gamma_{12} = \langle V_1^*(t) V_2(t + \tau_0) \rangle / (\langle I_1 \rangle \langle I_2 \rangle)^{1/2}$$

is the normalized cross-correlation function of the pump waves at the two crystals. R_s therefore exhibits interference as the phase difference $\theta_0 + \theta_2 - \theta_1$ is varied, with visibility

$$\mathcal{V} = \left[\frac{2 |f_1 f_2| \langle (I_1 \rangle \langle I_2 \rangle)^{1/2} |\gamma_{12}|}{|f_1|^2 \langle I_1 \rangle + |f_2|^2 \langle I_2 \rangle} \right] |\mathcal{T}|. \quad (6)$$

The factor in parentheses has the familiar form for interference of two waves, although it actually refers to the pump waves. It can be unity when $|f_1|^2 \langle I_1 \rangle = |f_2|^2 \langle I_2 \rangle$ and $|\gamma_{12}| = 1$. The visibility is, however, reduced below this value by the transmissivity $|\mathcal{T}|$. We note that all interference effects registered by D_s disappear when $|\mathcal{T}| = 0$, in which case the two idlers i_1, i_2 are effectively disconnected.

The experimental setup is shown in Fig. 1. Two similar 25-mm-long crystals of LiIO_3 are both optically pumped by the uv light of an argon-ion laser oscillating on the 351.1-nm line, which is divided by pump beam splitter BS_P . The emitted idler beams i_1, i_2 at 632.8 nm are aligned with the help of an auxiliary He:Ne laser, and the trajectories are defined by apertures. The two signal beams s_1, s_2 at 788.7 nm also pass through defining apertures and come together at the beam splitter BS_O , where they interfere. Cooled photon counting detectors D_s and D_i register the detected signal and idler photons, respectively. The photoelectric pulses from D_s and D_i , after amplification and shaping by A_s and A_i , are counted by scalars, and a coincidence counter with about 13-nsec resolving time registers coincidences between detected pulses. Typical counting rates are $R_i \sim 5000/\text{sec}$, $R_s \sim 400/\text{sec}$, and about 4/sec for the coincidence rate R_{si} . The output beam splitter BS_O is mounted on a piezoelec-

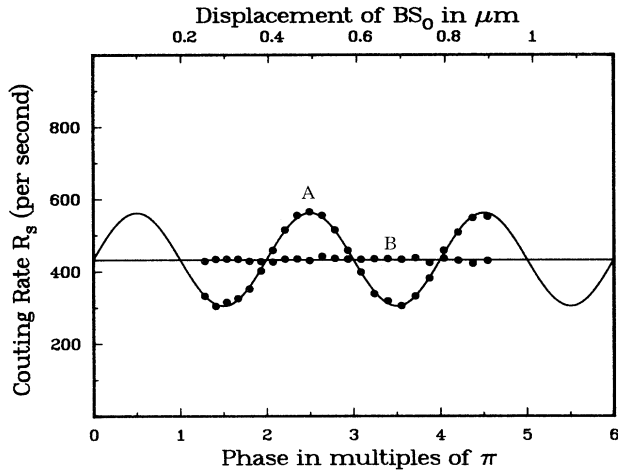


FIG. 2. Measured photon counting rate R_s as a function of beam-splitter BS_O displacement. Curve A : neutral-density filter with $|T|=0.91$ between NL1 and NL2; curve B : beam stop with $T=0$ inserted between NL1 and NL2. 1 standard deviation is smaller than the dot size. The solid curves are the best-fitting sinusoidal functions of period 394 nm.

tric transducer that allows submicron displacements to be made. The transducer in turn is attached to a stage that is movable with the help of a micrometer and stepping motor. The counting rates R_s , R_i , and R_{si} are measured as a function of the beam-splitter displacement. Interference filters IF_s and IF_i , centered at 788.7 and 632.8 nm, of about 10^{12} Hz bandwidth, placed in front of the detectors lengthen the coherence length of the detected down-converted light to about $\frac{1}{3}$ mm. Provision is made for inserting several different neutral-density filters NDF between NL1 and NL2 with various amplitude transmissivities $|T|$. The path differences between BS_P to NL1 to NL2 and BS_P to NL2 is kept well below the 5-cm coherence length of the uv pump beam.

The first step in the experiment is to equalize the path lengths NL1 to NL2 to D_s and NL1 to M_1 to D_s to within the 0.3-mm coherence length. This is accomplished by displacing BS_O successively in 50- μ m steps until an interference pattern of maximum visibility shows up in the coincidence-counting rate R_{si} . The visibility is then also maximized for second-order interference regis-

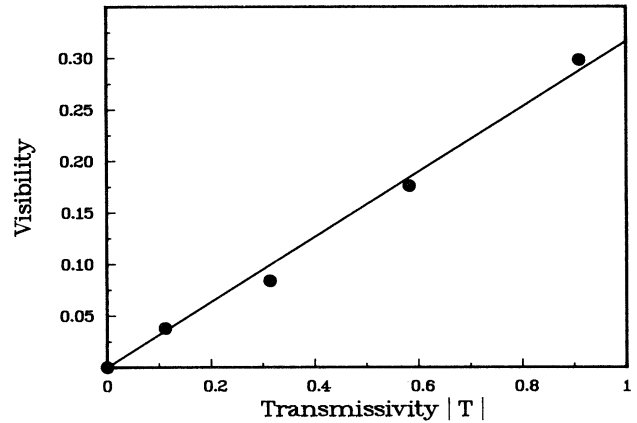


FIG. 3. Measured visibility \mathcal{V} of the second-order interference pattern as a function of amplitude transmissivity $|T|$ of the filter placed between NL1 and NL2. The uncertainties are comparable with or smaller than the dot size.

tered by D_s alone.

Figure 2 (curve A) shows the measured counting rate R_s of D_s as a function of beam-splitter BS_O displacement when $|T| \approx 0.91$. R_s exhibits second-order interference with about 30% visibility, as a result of the intrinsic indistinguishability of the s_1, s_2 photons. Next, we insert a succession of neutral-density filters of different amplitude transmissivity T between NL1 and NL2, and repeat the measurements. With the i_1 beam blocked completely ($T=0$) we obtain curve B in Fig. 2, which exhibits no interference. Figure 3 shows the measured visibility as a function of $|T|$, and we note that it is proportional to $|T|$ in agreement with Eq. (6). All interference effects vanish when the idlers i_1 and i_2 are effectively disconnected from each other.

This phenomenon appears strange here, because the photons are emitted spontaneously and at random by NL1 and NL2, so that one might not expect the interference exhibited by the signal photons to depend on the superposition of the idlers. Moreover, i_1 emission by NL1 and s_2 emission by NL2 almost never accompany each other. It is, however, possible to account for the observed $|T|$ dependence in terms of the state of the two signal photons. Let us use Eq. (3) to construct the density operator $\hat{\rho}_{\text{signal}}$ of the signal photons, by tracing over the i_1 and 0 modes. Then we obtain

$$\begin{aligned} \hat{\rho}_{\text{signal}} &= \text{Tr}_{i_1, 0} |\psi\rangle\langle\psi| \\ &= |\text{vac}\rangle_{s_1, s_2, s_1, s_2} \langle \text{vac} | + |f_1|^2 \langle I_1 | 1 \rangle_{s_1} |0\rangle_{s_2 s_2} \langle 0 |_{s_1} \langle 1 | \\ &\quad + |f_2|^2 \langle I_2 | 0 \rangle_{s_1} |1\rangle_{s_2 s_2} \langle 1 |_{s_1} \langle 0 | \\ &\quad + [T f_1 f_2^* V_1(t) V_2^*(t + \tau_0) e^{-i\theta_0} |1\rangle_{s_1} |0\rangle_{s_2 s_2} \langle 1 |_{s_1} \langle 0 | + \text{H.c.}] . \end{aligned} \tag{7}$$

The second and third terms on the right represent an incoherent mixture of one-photon states, but the last two terms proportional to $|T|$ describe a coherent superposition (singlet state) that gives rise to second-order interference. In a sense, i_1 has induced coherence between s_2 and s_1 without inducing emission in NL2. It is worth noting, however, that the state of the s_2 field alone is independent of T , as of course is the state of the s_1 field. This can be seen by tracing

both sides of Eq. (7) over the s_1 or s_2 variable. Because neither signal depends on \mathcal{T} , it is difficult to understand in classical terms why the second-order interference pattern produced by s_1 and s_2 depends on \mathcal{T} .

Finally, we return to the interpretation of the observation that second-order interference between s_1, s_2 disappears when the i_1, i_2 connection is broken or the two idlers are misaligned. It should be noted that the disappearance of the interference pattern here is not the result of a large uncontrollable disturbance acting on the system, in the spirit of the Heisenberg γ -ray microscope, but simply a consequence of the fact that the two possible photon paths s_1 or s_2 have become distinguishable. In quantum mechanics interference is always a manifestation of the intrinsic indistinguishability of the photon paths, in which case the corresponding probability amplitudes add. Because signal and idler photons are always emitted together, once the i_1, i_2 connection is broken it becomes feasible, in principle, to determine from the counts registered by an efficient detector D_i whether the detected signal photon comes from NL1 or NL2, and this destroys the interference. Whether or not this auxiliary measurement with D_i is actually made, or whether detector D_i is even in place, appears to make no difference. It is sufficient that it could be made, and that the photon path would then be identifiable, in principle, for the interference to be wiped out.

The experiment shows that induced emission need not accompany induced coherence, and it emphasizes that the state or density operator reflects not only what is known but to an extent also what could be known, in principle, about the photon.

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