# Induced Coherence and Indistinguishability in Optical Interference

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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

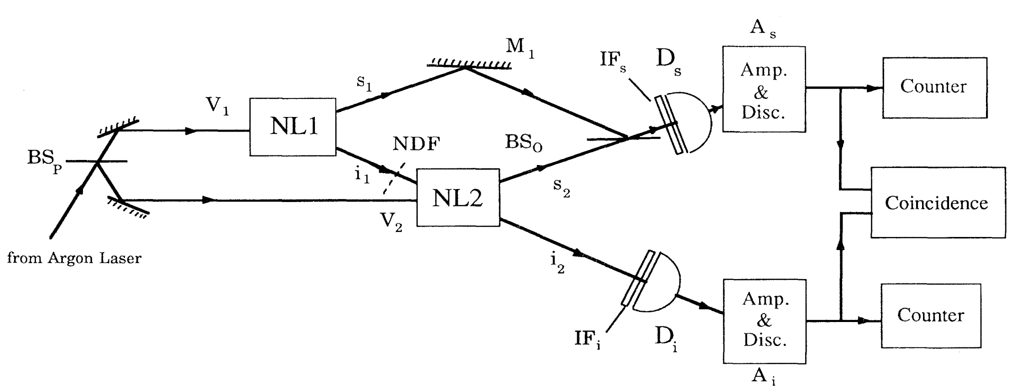


FIG. 1. Outline of the interference experiment.

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 $\omega_s$ and $\omega_i$, 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

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

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

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

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,

$$|\psi\rangle=|\text{vac}\rangle_{s_1,i_1,s_2,0}+f_1V_1(t)|1\rangle_{s_1}|1\rangle_{i_1}|0\rangle_{s_2}|0\rangle_0+f_2V_2(t+\tau_0)e^{-i\theta_0}(\mathcal{T}^*|0\rangle_{s_1}|1\rangle_{i_1}|1\rangle_{s_2}|0\rangle_0+\mathcal{R}^*|0\rangle_{s_1}|0\rangle_{i_1}|1\rangle_{s_2}|1\rangle_0)\,. \tag{3}$$

$|f_1|^2, |f_2|^2$ are the fractions of the incident light energy which are down-converted, $\tau_0$ is the propagation time from NL1 to NL2, and we have neglected terms with more than two photons.

We denote by $\theta_0$, $\theta_1$, and $\theta_2$ 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

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

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

$$R_s=|f_1|^2\langle I_1\rangle+|f_2|^2\langle I_2\rangle+2|f_1f_2|(\langle I_1\rangle\langle I_2\rangle)^{1/2}|\gamma_{12}||\mathcal{T}|\cos(\theta_0+\theta_2-\theta_1+\arg f_2-\arg f_1-\arg\mathcal{T}+\arg\gamma_{12})\,, \tag{5}$$

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

$$\mathcal{V}=\left(\frac{2|f_1f_2|(\langle I_1\rangle\langle I_2\rangle)^{1/2}|\gamma_{12}|}{|f_1|^2\langle I_1\rangle+|f_2|^2\langle I_2\rangle}\right)|\mathcal{T}|\,. \tag{6}$$

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 scalers, and a coincidence counter with about 13-nsec resolving time registers coincidences between detected pulses. Typical counting rates are $R_i\sim 5000$/sec, $R_s\sim 400$/sec, and about 4/sec for the coincidence rate $R_{si}$. The output beam splitter $BS_O$ is mounted on a piezoelec-

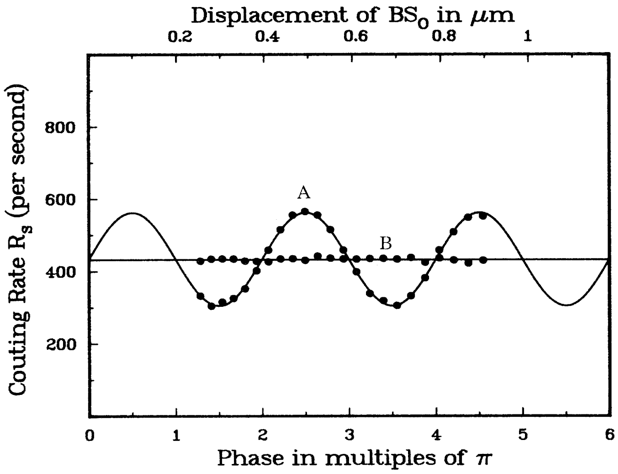


FIG. 2. Measured photon counting rate $R_s$ as a function of beam-splitter $BS_O$ displacement. Curve $A$: neutral-density filter with $|\mathcal{T}|=0.91$ between NL1 and NL2; curve $B$: beam stop with $\mathcal{T}=0$ inserted between NL1 and NL2. 1 standard deviation is smaller than the dot size. The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

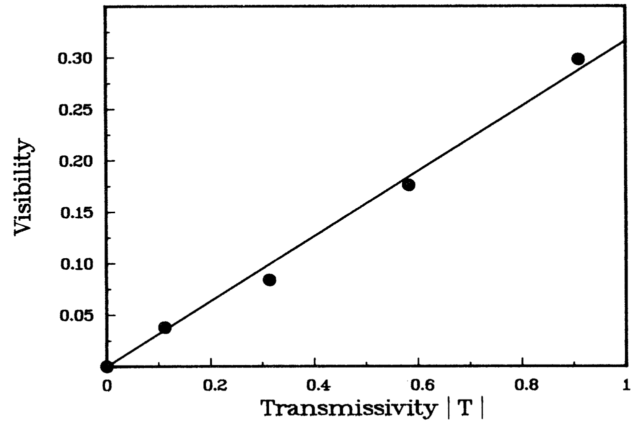


FIG. 3. Measured visibility $\mathcal{V}$ of the second-order interference pattern as a function of amplitude transmissivity $|\mathcal{T}|$ of the filter placed between NL1 and NL2. The uncertainties are comparable with or smaller than the dot size.

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 $|\mathcal{T}|$. 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-$\mu$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 registered 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 $|\mathcal{T}|\approx 0.91$. $R_s$ 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 $\mathcal{T}$ between NL1 and NL2, and repeat the measurements. With the $i_1$ beam blocked completely ($\mathcal{T}=0$) we obtain curve $B$ in Fig. 2, which exhibits no interference. Figure 3 shows the measured visibility as a function of $|\mathcal{T}|$, and we note that it is proportional to $|\mathcal{T}|$ 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 $|\mathcal{T}|$ 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

$$\begin{aligned}\hat{\rho}_{\text{signal}} &= \mathrm{Tr}_{i_1 0}|\psi\rangle\langle\psi| \\ &= |\text{vac}\rangle_{s_1,s_2\,s_1,s_2}\langle\text{vac}| + |f_1|^2\langle I_1\rangle|1\rangle_{s_1}|0\rangle_{s_2\,s_2}\langle 0|_{s_1}\langle 1| \\ &\quad + |f_2|^2\langle I_2\rangle|0\rangle_{s_1}|1\rangle_{s_2\,s_2}\langle 1|_{s_1}\langle 0| \\ &\quad + [\mathcal{T}f_1f_2^*V_1(t)V_2^*(t+\tau_0)e^{-i\theta_0}|1\rangle_{s_1}|0\rangle_{s_2\,s_2}\langle 1|_{s_1}\langle 0| + \text{H.c.}]\,. \end{aligned} \tag{7}$$

The second and third terms on the right represent an incoherent mixture of one-photon states, but the last two terms proportional to $|\mathcal{T}|$ 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 $\mathcal{T}$, 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 $\gamma$-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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