Photon antibunching by destructive two-photon interference

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A different way of producing antibunched light was experimentally demonstrated in which the production process is difficult to understand by a naive photon picture. A degenerate beam of down-converted photon pairs from a nonlinear crystal pumped by pulsed light was mixed with coherent local oscillator pulses by a beam splitter, and the intensity autocorrelation of one of the output beams was measured. It showed two-photon interference fringes as the phase difference of the two input fields was varied, and showed antibunching when the interference was destructive.

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Antibunching of photons is known as one of the nonclassical properties of light. It cannot be interpreted in terms of the classical electromagnetic theory which regards the light as a wave, but it is easily understood by a model of a flux of particles (photons) where the joint probability of finding two photons in time interval τ becomes smaller as τ goes to zero. In this sense, photon antibunching reflects the corpuscular nature of light [1]. Experimentally it was first observed by Kimble *et al.* [2] and has since been observed in other ways also [3–9]. Several methods have been used to generate antibunched light in these experiments. In the experiments using resonance fluorescence from a small number of atoms or molecules [2–7], each atom (molecule) goes back to its lower state after the emission of a photon, and the probability of emitting a second photon successively becomes small. In the experiment using twin beams and a detection-triggered shutter [8], the production of a photon in the signal beam is inferred by the detection at the idler beams, and right after the photon is detected the shutter is closed to forbid production of successive photons. In the experiment using parametric amplification [9], two photons are simultaneously eliminated from an incoming coherent light beam through the nonlinear interaction in the crystal. Thus in these experiments not only the observation of antibunching but also the production process of antibunched light can be understood at least qualitatively in terms of the particle model.

In this paper, we report on the result of an experiment in which antibunched light was produced in a new scheme in which it is difficult to understand the production process in the simple particle model. Parametrically down-converted photons, which have a strong bunching property, were mixed with coherent light with a proper intensity and phase by a beam splitter, and one of the output beams showed antibunching. Theoretically, Ritze and Bandilla appear to be the first to mention this scheme [10].

The principle of the experiment is shown in Fig. 1. A coherent laser beam at frequency ω is injected into a crystal for second-harmonic generation (SHG). The second harmonic at frequency 2ω is used as the pump field of a degenerate optical parametric down-converter (PDC). The residual fundamental light at frequency ω after SHG is properly attenuated and used as a local oscillator (LO). The down-converted photons (DC) and the LO are mixed by a 50%:50% beam splitter (BS1) with a proper phase delay. Intensity correlation of one of the output beams is measured by dividing it into two parts by another beam splitter (BS2) and measuring delayed coincidence at two detectors (D1, D2).

The actual experiment was carried out by the apparatus shown in Fig. 2. It is similar to the previous experiment for observation of two-photon interference between down-converted photons and a local oscillator [11]. A cw mode-locked Nd^{3+}-doped yttrium aluminum garnet laser (Spectron model ML903) generates linearly polarized infrared pulses at 1.064 μm with full width at half maximum $\sim$100 psec at a repetition rate of 82 MHz. The fundamental light is injected into a LiB_3O_5 crystal which is noncritically type-I phase matched by controlling the temperature, and the second-harmonic light ($\sim$100 mW) emerges in the same direction as the residual fundamental light. The harmonic is used as a pump field for a single-pass degenerate PDC made of a 5.8-mm-long $KNbO_3$ crystal. The PDC crystal is also noncritically type-I phase matched by controlling the temperature, and down-converted photons are emitted as an ordinary ray. The residual fundamental light is used as an LO after its intensity is adjusted by a harmonic wave plate

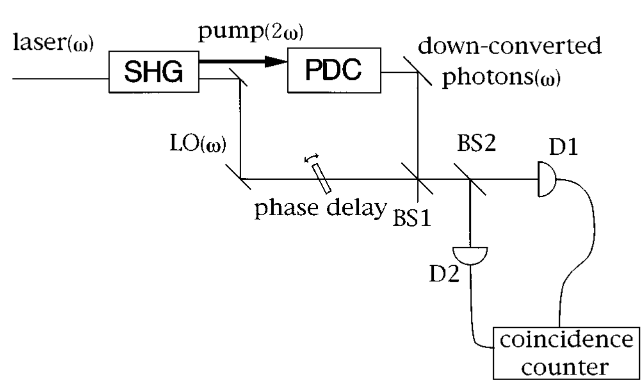

FIG. 1. Principle of the experiment.

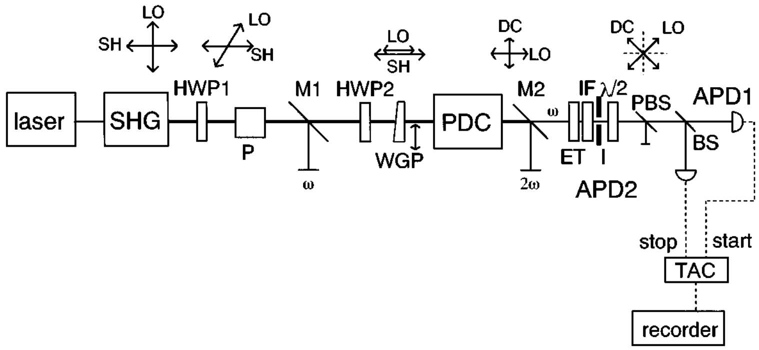

FIG. 2. Schematic drawing of the experimental apparatus. HWP1-2, harmonic wave plates; M1-2, mirrors; WGP, wedged glass plate; P, polarizer; PDC, parametric down-converter; ET, étalon; IF, interference filter; I, iris; λ/2, half wave plate; PBS, polarizing beam splitter; BS, beam splitter; APD1-2, photon-counting avalanche photodiodes; TAC, time-to-amplitude converter. Arrows show the direction of polarization of local oscillator (LO), pump (SH), and down-converted photons (DC).

(HWP1), a polarizer (P), and harmonic mirrors (M1) [9]. The phases of the LO and the pump are varied by displacement of a wedged BK-7 glass plate (WGP) with different refractive indices for the two frequencies. The LO is then injected into the PDC crystal as an extraordinary ray so that it experiences no parametric interaction. Note that the injection of the LO into the PDC crystal is merely for the stabilization of the relative phase between the LO and the down-converted photons, and the setup is definitely different from the one in Ref. [9] in which the coherent light underwent parametric interaction in the crystal. After the PDC, the pump is eliminated by a mirror and filters (M2). The LO and the down-converted light pass through an interference filter (IF), a solid étalon (ET), and an iris. The étalon has a free spectral range of 240 GHz with a finesse ~60. The orthogonally polarized LO and down-converted photons are mixed by a polarizing beam splitter (PBS), which works as BS1 in Fig. 1. By changing the angle (Θ) of the λ/2 wave-plate axis, we can choose either the LO ($\Theta=0°$), the down-converted light ($\Theta=45°$), or 50%:50% mixed light of them ($\Theta=22.5°$) to emerge from the output of the PBS. The output beam is divided into two by a beam splitter (BS) and photon counting is performed at the two outputs of the BS by silicon avalanche photodiodes (APD, RCA model SPCM-100-PQ, quantum efficiency at 1.06 μm~0.8%). Their outputs are fed to the start and the stop inputs of a time-to-amplitude converter (TAC).

Since the temporal resolution of the detectors is slower than the pulse width, we have to regard the start and stop events in a single mode-locked pulse as coincidence. In this case, what we measure as normalized intensity correlation is that of pulses of the nth neighbor:

$$g_n^{(2)} \equiv \frac{\left\langle \mathscr{T}\!: \int \hat{I}(t)dt \int \hat{I}(t+nT)dt \!: \right\rangle}{\left\langle \int \hat{I}(t)dt \right\rangle \left\langle \int \hat{I}(t+nT)dt \right\rangle}, \tag{1}$$

where $\hat{I}(t)$ is the intensity operator of the output light of the PBS, the operator product is written in normal order and in time order, T is the time interval of the pulses, and the integrations run over the duration of a single pulse. Observed light has a bunching property when $g_0^{(2)} > g_n^{(2)}$ and antibunching when $g_0^{(2)} < g_n^{(2)}$ $(n \neq 0)$ [9].

Figures 3(a)–3(c) represent the number of photon pairs as a function of time delay recorded for the three choices of the axis angle Θ of the λ/2 plate. The data consists of peaks at 12.2 nsec ($=T$) intervals corresponding to the repetition rate of the mode-locked laser. The width of each peak is determined by the temporal resolution of the detectors. Hence, the total number of counts in a single peak rather than the height of the peak is relevant. We denote the total number of coincidence counts in the peak at time delay nT by $G_n^{(2)}$. We also recorded singles counting rates R_1 and R_2 at the two detectors and the number of the start pulses which actually activate TAC in each run of the experiment. We separately measured the contribution of background to be $r_1=790$/sec and $r_2=1100$/sec at the two detectors, which mainly consist of the dark counting of the detectors. We can calculate the normalized intensity correlation $g_n^{(2)}$ from these data [9]. For $n \neq 0$, the calculated $g_n^{(2)}$ in Figs. 3(a)–3(c) were all unity except for the deviation due to the statistical error.

Figure 3(a) represents the intensity correlation of LO. The net counting rates at the two detectors were $\mathscr{R}_1 \equiv R_1 - r_1 = 1.30 \times 10^4$/sec and $\mathscr{R}_2 \equiv R_2 - r_2 = 1.42 \times 10^4$/sec. For the measurement time of 1000 sec, $G_0^{(2)}$ was 2585 counts. The calculated $g_0^{(2)}$ was then 1.02 ± 0.02. This shows that there is no correlation between two photon-counting events, as expected for coherent light. Figure 3(b) shows the intensity correlation of the down-converted photons. They show prominent bunching, i.e., the probability of finding two photons in a single pulse is much larger than in neighboring pulses. This reflects the characteristics of the parametric down-conversion process in which a single pump photon is split into two converted photons [12]. The net counting rates were $\mathscr{R}_1 = 2.3 \times 10^3$/sec and $\mathscr{R}_2 = 2.5 \times 10^3$/sec, and the total coincidence counts $G_0^{(2)} = 929$ for 2000 sec. The normalized value $g_0^{(2)}$ was calculated to be 5.95 ± 0.06. When we set the λ/2 plate at $\Theta = 22.5°$, these two beams are mixed at the PBS. The intensity correlation of the mixed light is shown in Fig. 3(c). The phase difference between the LO and the down-converted photons was adjusted by moving the WGP to minimize the coincidence counting rate (see Fig. 4). The

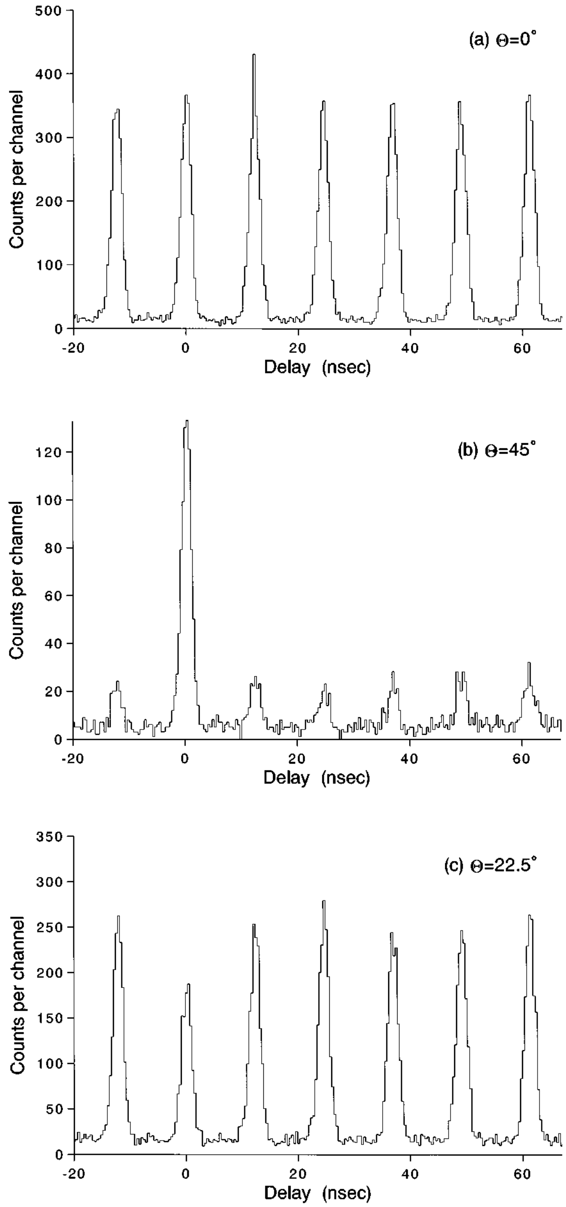

FIG. 3. Number of recorded photon pairs as a function of time delay. The channel width is 0.183 nsec. They represent the intensity correlation of (a) the coherent light (the local oscillator), (b) the down-converted light, and (c) the superposition of them. The data taking time is 1000 sec for (a), and 2000 sec for (b) and (c).

measured data show clearly that the probability of finding two photons in a single pulse of the mixed light is smaller than in different pulses; that is, it has an antibunching property. The net counting rates were $\mathscr{R}_1=7.7\times10^3$/sec and $\mathscr{R}_2=8.3\times10^3$/sec, and the total coincidence counts $G_0^{(2)}=1532$ for 2000 sec. We calculated $g_0^{(2)}$ to be 0.74 ± 0.03. This value is smaller than unity, which means the statistics of photon number in a single pulse of the mixed light are sub-Poissonian.

The observed properties, antibunching and sub-Poissonian, are both nonclassical in that they cannot be understood by the classical treatment of the electromagnetic field. They are the properties representing the corpuscular nature of light. Let us then try to understand the production

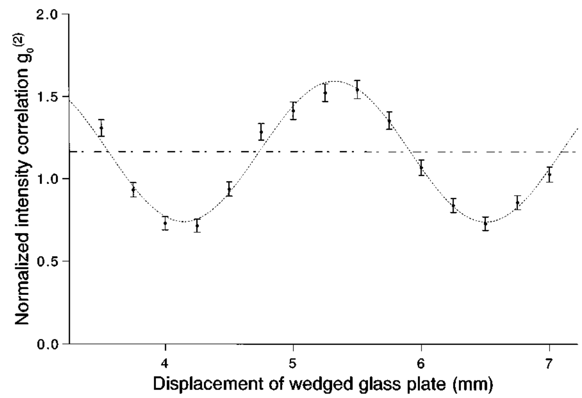

FIG. 4. Observed normalized intensity correlation $g_0^{(2)}$ as a function of displacement of the wedged glass plate.

process of the above antibunched light qualitatively by assuming that the light is the flow of particles. In this model the down-converted light is the flow of bunched particles, and the LO is the flow of random particles. These two flows originally branch at the SHG process in which a single pulse of the incident light has 10^{10} photons, and the intensity of the LO is significantly reduced by the mirrors (M1) and that of the down-converted light by the low conversion efficiency of the PDC before they reach the inputs of the beam splitter (PBS). This allows us to neglect any correlation of particles between the two flows. Then, when they are superposed by the beam splitter, it is expected that the degree of bunching will be reduced from that of the down-converted light by the mixing of random particles of the LO, but the mixed flow will never show antibunching. In fact, this model predicts $g_0^{(2)}=1.11$ for the superposed light using the observed $\mathscr{R}_1$, $\mathscr{R}_2$, and $g_0^{(2)}$ for both the LO and the down-converted light case. Thus, the simple particle model has a severe difficulty in explaining the above experiment. Actually, the antibunching is caused by a wavelike interaction, as seen below.

Figure 4 is the plot of measured $g_0^{(2)}$ of the mixed light ($\Theta=22.5°$) when the phase difference between the LO and the down-converted light was varied through the displacement of the WGP. The singles counting rates do not depend on the phase difference because the down-converted light does not have a definite phase. The random fluctuations of the counting rates ($\sim$4%) are compensated through the normalization. Each data point corresponds to 500 sec of data taking. It is seen that the measured values clearly form interference fringes. The broken curve in Fig. 4 is sinusoidal curve adjusted for best fit. It has the same periodicity as that of the parametric gain that can be observed when HWP2 is turned by 45° so that the LO is injected into the PDC as an ordinary ray. This means that the periodicity of the fringe corresponds to the wavelength of pump light. It is also in good agreement with the refractive index difference of BK-7 between the two frequencies, $\Delta n=0.012$, and the wedge angle, $\sim1°$, of the WGP. The averaged normalized intensity correlation, the level shown by the dash-dotted line in Fig. 4, is 1.17, and this value is close to the one predicted by the above particle model. The coincidence rates increase or decrease from this value by interference depending on the phase difference. When the interference is destructive, the normalized correlation $g_0^{(2)}$ decreases below unity and the mixed light shows antibunching. Thus, we may conclude that in the present experiment the particlelike property, antibunching, originates from a wavelike interference.

It should be noted that the experimental setup in Ref. [9] formed a simple amplification line of coherent light, and cannot be unfolded to a two-arm interferometor like in Fig. 1. Thus, in that case, the interpretation by the simple particle picture that the photons were removed in pairs in the crystal was valid.

In quantum mechanics, underlying physics of the present experiment may be understood as follows. When we assume that each light beam is in a single mode and neglect the contribution from more than three photons, the state $|\Psi_{\rm in}\rangle$ at the input of BS1 in Fig. 1 is represented by the direct product

$$|\Psi_{\rm in}\rangle = |\Psi_{\rm LO}\rangle_0 |\Psi_{\rm DC}\rangle_1 \tag{2}$$

in which $|\Psi_{\rm LO}\rangle_0$ is a coherent state with a complex amplitude α,

$$|\Psi_{\rm LO}\rangle_0 = K_a\left[\frac{\alpha^2}{\sqrt{2}}|2\rangle_0 + \alpha|1\rangle_0 + |0\rangle_0\right], \tag{3}$$

and $|\Psi_{\rm DC}\rangle_1$ is a linear superposition of the two-photon state $|2\rangle$ and the vacuum $|0\rangle$,

$$|\Psi_{\rm DC}\rangle_1 = K_b\left[\frac{\zeta}{\sqrt{2}}|2\rangle_1 + |0\rangle_1\right], \tag{4}$$

where ζ is a complex value proportional to the complex amplitude of the pump light. K_a and K_b are real constants for normalization, and the subscripts 0 and 1 indicate the two input modes of BS1. The output state $|\Psi_{\rm out}\rangle$ is calculated from the relation between input and output states at the beam splitter [13]. If we assume the reflectivity and the transmissivity of BS1 to be both 1/2, the result is

$$\begin{aligned}|\Psi_{\rm out}\rangle = K_aK_b\Bigg[&\frac{\alpha^2-\zeta}{2\sqrt{2}}|2\rangle_2|0\rangle_3 - \frac{\alpha^2-\zeta}{2\sqrt{2}}|0\rangle_2|2\rangle_3\\ &- \frac{i(\alpha^2+\zeta)}{2}|1\rangle_2|1\rangle_3 + \frac{\alpha}{\sqrt{2}}|1\rangle_2|0\rangle_3 - \frac{i\alpha}{\sqrt{2}}|0\rangle_2|1\rangle_3\\ &+ |0\rangle_2|0\rangle_3\Bigg],\end{aligned} \tag{5}$$

where we assume that α^2 and ζ are of the same order and keep only the terms of order α^2 or lower. The subscripts 2 and 3 denote the two output modes. The normalized intensity correlation $g^{(2)}$ of the mode 2 is, up to the leading terms,

$$\begin{aligned}g^{(2)} &\equiv \frac{\langle\Psi_{\rm out}|\hat{a}_2^\dagger\hat{a}_2^\dagger\hat{a}_2\hat{a}_2|\Psi_{\rm out}\rangle}{\langle\Psi_{\rm out}|\hat{a}_2^\dagger\hat{a}_2|\Psi_{\rm out}\rangle^2} = \frac{|\alpha^2-\zeta|^2}{|\alpha|^4}\\ &= 1 - \frac{2|\alpha|^2|\zeta|\cos(2\theta-\phi) - |\zeta|^2}{|\alpha|^4},\end{aligned} \tag{6}$$

where $\alpha = |\alpha|e^{-i\theta}$ and $\zeta = |\zeta|e^{-i\phi}$. $g^{(2)}$ varies sinusoidally as the phase difference changes, and decreases below unity at the trough when $|\alpha|^2 > |\zeta|/2$. The interference arises because two probability amplitudes of finding two photons in mode 2 are added in the first term of Eq. (5). Thus, the origin of antibunching in our experiment is the destructive interference of the two possible ways of coincidence events. It is worth noting that the interference in the intensity [the denominator of Eq. (6)] does not take place, since the down-converted light and the local oscillator are mutually incoherent.

In the present study we used pulsed light. It is essential, as in the previous experiment [11], for the observation of antibunching when the resolution of the detectors is poor in comparison to the reciprocal bandwidth of the étalon. The use of weaker light and/or the use of a narrower frequency filter would help observation of a more prominent antibunching.

In conclusion, we mixed coherent light and parametrically down-converted light with a beam splitter, and measured the intensity correlation of the superposed light. It revealed interference fringes as the phase difference between the two light fields was varied, which is a wavelike phenomenon. At the same time, the trough of the fringe indicated antibunching, which is a particlelike phenomenon. In quantum mechanics, the effect was understood as the interference between two possible ways of detecting two photons coincidentally. It is noteworthy that the present technique provides the light source with variable $g^{(2)}$ while the intensity is fixed.

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