Spectral Hong-Ou-Mandel Effect between a Heralded Single-photon State and a Thermal Field: Multiphoton Contamination and the Nonclassicality Threshold

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The Hong-Ou-Mandel (HOM) effect is crucial for quantum information processing, and its visibility determines the system's quantum-classical characteristics. In an experimental and theoretical study of the spectral HOM effect between a thermal field and a heralded single-photon state, we demonstrate that the HOM visibility varies dependent on the relative photon statistics of the interacting fields. Our findings reveal that multiphoton components in a heralded state get engaged in quantum interference with a thermal field, resulting in improved visibilities at certain mean photon numbers. We derive a theoretical relationship for the HOM visibility as function of the mean photon number of the thermal field and the thermal part of the heralded state. We show that the non-classicality degree of a heralded state is reflected in its HOM visibility with a thermal field; Our results establish a lower bound of 41.42% for the peak visibility, indicating the minimum assignable degree of nonclassicality to the heralded state. This research enhances our understanding of the HOM effect and its application to high-speed remote secret key-sharing, addressing security concerns due to multiphoton contamination in heralded states.

Introduction. __ Large-scale quantum networks enable secure remote transfer of quantum states. Such capability relies on highly efficient, noise-resistant, and robust quantum internet components [1], ranging from quantum end-nodes to interconnects and repeaters [2,3]. At the heart of a quantum network lies the Hong-Ou-Mandel (HOM) effect [4–7] which involves destructive quantum interference at a balanced beam splitter of both-reflected and both-transmitted two-photon amplitudes. Frequency encoding is a promising platform for global quantum networks, thanks to its parallelizability, phase-stability, noise-resilience , and compatibility with modern telecommunications infrastructure [8,9]. Moreover, frequency allows for reversible conversion of quantum states among various physical systems within a quantum network [10,11]. Recent advancements include a scalable realization of the spectral HOM effect between independent single-photon states [12]. The HOM effect underpins the development of measurement-device-independent quantum key distribution (MDI-QKD) protocols, addressing the side-channel security gaps [13–16] and in particular, implemented between imperfect single-photon sources – such as heralded states from spontaneous parametric down-conversion (SPDC) [17] – and weak classical states [16,18–21]. To enable quantum interference, preparing single-mode heralded single-photon states involves eliminating frequency correlations. This introduces thermal characteristics to the state, the impact of which has not been explicitly studied on the HOM visibility. We experimentally implement the spectral HOM effect between a thermal field and a heralded single-photon state from pulsed-excited SPDC process. We analyze the impact of multiphoton contamination in imperfect single-photon states on the HOM visibility. Importantly, our findings reveal that multiphoton components in a heralded state contribute to quantum interference with the thermal field. This observation, questions the common assumption that multiphoton components in a heralded state exclusively degrade the visibility, hence subtracted from the coincidence counts (CC) [22]. This study provides fundamental insight into the link between the HOM visibility and photon statistics of the interacting fields, with potential application in ascertaining security in high-speed remote secret key sharing [23].

Theoretical derivation of visibility in the HOM interference between a thermal field and a heralded state. ___ In a pulsed-driven SPDC process with a two-mode squeezer (**FIG. 1**), a single detection in the signal mode s1 (on detector D3) heralds the existence of at least one photon in the idler mode i1 (on detector D1), resulting in a heralded state in the latter mode. The first- and the second-order moments associated with the heralded state are

$$\langle \hat{a}^\dagger \hat{a} \rangle_{i1} = \mathrm{Tr}\,\{\hat{a}_{i1}^\dagger \hat{a}_{i1}\, \tilde{\rho}^i\} = \bar{n}_{i1,\mathrm{th}} + 1$$
$$\langle \hat{a}^{\dagger 2} \hat{a}^2 \rangle_{i1} = \mathrm{Tr}\,\{\hat{a}_{i1}^{\dagger 2}\, \hat{a}_{i1}^2\, \tilde{\rho}^i\} = 2\bar{n}_{i1,\mathrm{th}}^2 + 2\bar{n}_{i1,\mathrm{th}} \qquad (1)$$

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where $\tilde{\rho}^i$ is the normalized density matrix describing the heralded state (see **Appendix A**). The $\hat{a}_{i1}^{\dagger}$ and $\hat{a}_{i1}$ are the photon creation and annihilation operators, respectively, and $\bar{n}_{i1,th}$ represents the average photon number per pulse period within the thermal part of the heralded state, i.e., the multiphoton components. The thermal field is created in the idler frequency mode i2 from an independent SPDC process and by discarding the detections on its twin signal frequency mode (See **FIG. 1**). From equation (1), the second-order correlation between the thermal field and the heralded state is derived as function of photons' arrival times t and t' at the detectors (See **Appendix B**)

$$g^{(2)}_{i1,i2}(t,t') = 2\bar{n}^2_{i1,th} + 2\bar{n}^2_{i2} + 2\bar{n}_{i1,th} + 2\bar{n}_{i2}(\bar{n}_{i1,th} + 1)(1 - \delta_{i1,i2}) \quad (2)$$

with $\bar{n}_{i2}$ as the mean photon number per pulse period of the thermal field triggered by detections on s1. The modulation coefficient $\delta_{i1,i2} \in [0,1]$ depends on the fields' degree of indistinguishability. From (2) we derived a new relationship between the HOM visibility and $\bar{n}_{i1,th}$ and $\bar{n}_{i2}$ (See **Appendix B**):

$$V_{theory} = \frac{1}{1 + \frac{\bar{n}^2_{i1,th} + \bar{n}^2_{i2} + \bar{n}_{i1,th}}{\bar{n}_{i1,th}\,\bar{n}_{i2} + \bar{n}_{i2}}} \quad (3)$$

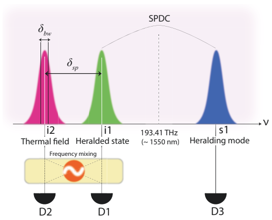

FIG. 1. Spectral configuration of the spectral HOM experiment between a thermal field (i2: red) and a heralded single-photon state (i1: green); Electro-optic phase modulation (frequency mixing) is applied between i1 and i2. (Insertion loss: 2.8 dB, δ_{sp} = 75 GHz; δ_{bw} = 22 GHz; rf tone Ω = 25 GHz; rf power amplitude: -10 dB; ν: frequency axis)

Experimental implementation of the HOM effect between a thermal field and a heralded state. __ The experimental setup (See **FIG. 2**) includes a mode-locked laser (*Menlo Systems*) with 50 MHz repetition rate, centered at λ_{pump}= 774.93 nm wavelength, and filtered to full-width at half-maximum $FWHM_{pump}$ = 200 GHz. A 40 mm-long, 5% MgO-doped PPLN waveguide (*Covesion*) is used to create time-energy correlated signal-idler photon pairs via SPDC, centered around the degeneracy point λ_{deg} ~1550 nm. The spectral configuration (See **FIG. 1**) was adjusted using a programmable filter (*Finisar Waveshaper 4000S; insertion loss: 4.5dB*) to guarantee high spectral purity of the photons (single-mode bandwidth δ_{SMB} ~ 50 GHz; See HBT interferometry in **Appendix C**. & Refs. [12,24–27]). Electro-optic phase modulation (EOPM; *EO Space*) is used to half split the power between the heralded state (i1) and the thermal field (i2) enabling to probe the HOM effect in frequency (See Refs. [12,28] and **Appendix D**). The sidebands are generated at 25 GHz free spectral range and band-pass filtered to maintain the experiment's spectral configuration. Coincidence events are recorded at integer multiples of the 20 ns pulse period via a timing electronics module (*Swabian instruments; Timetagger Ultra*).

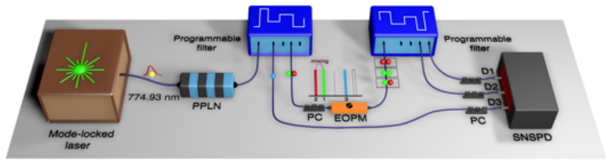

FIG. 2 Experimental setup of the spectral HOM effect between a thermal field and a heralded state. A single excitation photon (yellow) is sent through a PPLN waveguide and decays into pairs of correlated signal-idler photons. The system's spectral configuration is defined at the first programmable filter. The idler photon i1 (green) is heralded by the detection of its twin photon in the signal mode s1 (blue), and the idler mode i2 (red) is detected independently but triggered by detections on s1. Electro-optic phase modulation is applied on the idler modes i1 and i2, and the coincidence detections are collected on detectors D1 (monitoring i1), D2 (monitoring i2), and D3 (monitoring s1). (PC; polarization controller, EOPM; electro-optic phase modulator, SNSPD; superconducting nanowire single photon detector).

Experimental retrieval of visibility for the HOM effect between a thermal field and a heralded state. ___ The experimental result of the spectral HOM effect is shown in **FIG. 3**. The three-fold coincidence counts are displayed versus delay – expressed as integer multiples of the pulse period ($\Delta t = m \times T$; T = 20 ns; m = 0, ±1, ±2, ...) – between D2 and the heralded detections on D1. In general, visibility in the HOM effect is probed by contrasting the number of two-photon amplitudes of indistinguishable photons (from two input modes of a beam splitter) that bunch in the output modes, to those of distinguishable photons that emerge as coincidence detections, the latter considered as reference point CC_{ref}. Distinguishability is achievable by introducing non-zero delay values Δt between the photons. In conventional HOM setups [22,29], temporal distinguishability is realized between the two input modes of a beam splitter via an optical delay line. Unlike such approaches where the average delayed coincidence counts serve as the reference point $CC_{ref} = CC^{ave}(\Delta t \neq 0)$, the *inter-pulse* delay principle ($\Delta t = m \times T$; T = 20 ns; m = 0, ±1, ±2, ...) adopted in our experiment necessitates considering additional coincidence counts to determine CC_{ref} (See **Appendix E**). Such enhancement in CCs associates with the thermal statistics of multiphoton components in the heralded state. We can distinguish three contributions: The three-fold CCs from photons residing prior to phase modulation in different input modes $\mathrm{CC}_{i2,i1|s1}$, from multiphoton components within the thermal field $\mathrm{CC}_{i2,i2|s1}$, and from multiphoton components within the heralded state $\mathrm{CC}_{i1,i1|s1}$. The reference point is thus written

$$\mathrm{CC}_{\mathrm{ref}} = \mathrm{A} \times \mathrm{CC}_{i1,i1|s1}(\Delta t \neq 0) + \mathrm{B} \times \mathrm{CC}_{i2,i2|s1}(\Delta t \neq 0) + \mathrm{C} \times \mathrm{CC}_{i2,i1|s1}(\Delta t \neq 0). \quad (4)$$

The HOM visibility $\mathrm{V}_{\mathrm{exp}}$ is obtained through

$$V_{\mathrm{exp}} = (\mathrm{CC}_{\mathrm{ref}} - \mathrm{CC}(0))/\mathrm{CC}_{\mathrm{ref}} \quad (5)$$

with CC(0) as the three-fold coincidence counts measured at zero delay ($\Delta t = 0$). On the right-hand side of equation (4), D1 and D2 detect photons exclusively emitted from i1 (first term), exclusively from i2 (second term), and from both i1 and i2 (third term). The enhancement coefficients $\mathrm{A} = g^{(2)}_{i1,i1|s1}(0)$ and $\mathrm{B} = g^{(2)}_{i2,i2|s1}(0)$, which account for the additional CCs introduced by multiphoton components, are defined as the unconditional second-order auto-correlation functions

$$g^{(2)}_{i1(i2),i1(i2)|s1}(0) = \mathrm{CC}_{i1(i2),i1(i2)|s1}(0)/\mathrm{CC}_{i1(i2),i1(i2)|s1}(\Delta t \neq 0). \quad (6)$$

The enhanced CCs result from high spectral purity and temporal indistinguishability at zero delay, essential for implementing the HOM effect [24,30,31]. By exclusively allowing the emission from i1 (i2) and s1 to pass through the first programmable filter, the unconditional second-order auto-correlation function A = 1.98±0.1 (B≈2) for the heralded-state in i1 (thermal field in i2) is measured (See **Appendix F**), which confirms the single frequency-mode assumption. However, the contribution from the second term is found negligible for the delayed and non-delayed events ($\mathrm{CC}_{i2,i2|s1}(\Delta t \neq 0) \approx \mathrm{CC}_{i2,i2|s1}(\Delta t = 0) \approx 0$) which ascribes to three SPDC processes per pulse. For the last term we obtain C = 1, namely, the three-fold coincidence detections from two different input modes i1 and i2, emerge at an identical delayed and non-delayed rate, $\mathrm{CC}_{i2,i1|s1}(\Delta t \neq 0) = \mathrm{CC}_{i2,i1|s1}(\Delta t = 0)$. This owes to the fact that generation in i1 and i2 emerge from two different SPDC processes. Since the separation bandwidth between i1 and i2 exceeds the single-mode bandwidth (50 GHz; See **Appendix C**), i1 and i2 are considered independent spectral modes. As a result, the generation rate of photons in i1 and i2, whether in different pulses or the same pulse, is identical. In this experiment, the average delayed three-fold coincidence counts are measured $\mathrm{CC}^{\mathrm{ave}}(\Delta t \neq 0) = 484 \pm 22$, which consists in the following events: $\mathrm{CC}^{\mathrm{ave}}(\Delta t \neq 0) = \mathrm{CC}^{\mathrm{ave}}_{i1,i1|s1}(\Delta t \neq 0) + \mathrm{CC}^{\mathrm{ave}}_{i2,i1|s1}(\Delta t \neq 0)$; The contribution of each constituent term is obtained by having access to the generation ratio $\bar{n}_{i1,th}/\bar{n}_{i2} \approx 1.02$ between the mean photon number per pulse period of the thermal part of the heralded state, $\bar{n}_{i1,th}$, and the thermal field, $\bar{n}_{i2}$ (See **Appendix G**). From this ratio the first $\mathrm{CC}^{\mathrm{ave}}_{i1,i1|s1}(\Delta t \neq 0) \approx 245$ and second terms $\mathrm{CC}^{\mathrm{ave}}_{i2,i1|s1}(\Delta t \neq 0) \approx 239$ are retrieved. From equation (4), the reference point $\mathrm{CC}_{\mathrm{ref}} \approx 724 \pm 45$ is thus determined. From the measured coincidence counts at zero delay, $\mathrm{CC}(0) = 411 \pm 20$, the experimental HOM visibility, $\mathrm{V}_{\mathrm{exp}} = 43.2\% \pm 4.3\%$, is calculated.

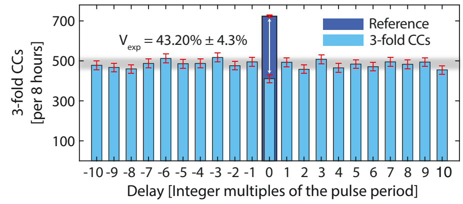

FIG. 3. Results from the spectral HOM experiment between a thermal field and a heralded state: Three-fold coincidence counts as function of delay between detectors D1 and D2 – triggered by single detections on D3. The grey line shows the average number of delayed coincidence counts $CC^{ave}(\Delta t \neq 0) = 484 \pm 22$. The arrow shows the experimental value for HOM visibility, $V_{exp} = 43.2\% \pm 4.3\%$, defined as the difference between the reference point, $CC_{ref} = 724 \pm 45$, and the coincidence counts measured at zero delay, $CC(0) = 411 \pm 20$. The error bars show the standard deviation (square root) of the coincidence counts per 8-hour integration time.

Validating the experimental results. __ Assuming P(n) as the probability of having n heralded photons per heralding detection, for a heralded state characterized by $\mathrm{P}(1) \gg \mathrm{P}(2) \gg \mathrm{P}(n>2)$, the following relations hold true [31]

$$g_h^{(2)}(0) \approx 2\mathrm{P}(2)/\mathrm{P}(1)^2$$

$$\mathrm{P}(0) + \mathrm{P}(1) + \mathrm{P}(2) + \mathrm{P}(n > 2) = 1, \quad (7)$$

where $g_h^{(2)}(0) \approx 0.25$ is the measured heralded auto-correlation function (See **Appendix H**). In our system for $n > 2$ we assume $\mathrm{P}(n > 2) \approx 0$. In addition, we have $\mathrm{P}(0) \approx 0$, which denotes zero probability of occupation in the vacuum state for a heralded state. From equation (7) the probabilities $\mathrm{P}(1) \approx 0.89$ and $\mathrm{P}(2) \approx 0.1$ are determined. Followed by $\bar{n}_{i1} = \mathrm{Tr}\{\hat{\rho}_{i1}\hat{n}_{i1}\}$ with $\bar{n}_{i1}$ as the mean photon number in the heralded state, $\hat{n}_{i1}$ as the photon number operator, and $\hat{\rho}_{i1} = \sum_n \mathrm{P}(n)\,|n\rangle\langle n|$ as the density matrix of the heralded state, $\bar{n}_{i1} = \mathrm{P}(1)+2\mathrm{P}(2)$ is yielded, hence $\bar{n}_{i1} \approx 1.1$. Subtraction of the single-photon contribution from $\bar{n}_{i1}$ gives $\bar{n}_{i1,th} \approx 0.1$. The generation ratio

$\bar{n}_{i1,th}/\bar{n}_{i2} \approx 1.02$ thus gives $\bar{n}_{i2} \approx 0.098$. By replacing $\bar{n}_{i1,th}$ and $\bar{n}_{i2}$ in equation (3), the visibility $V_{theory} = 47.3\% \pm 0.7\%$ for the HOM effect between the heralded state and the thermal field is obtained, which is in good agreement with the experimental result from the previous section.

Discussion. __ By definition the HOM effect is considered as a two-photon bunching effect that results from the superposition on a balanced beam splitter of two indistinguishable photons, coming from different input modes of the beam splitter. This definition establishes the presumption of full involvement in the HOM effect – under perfect indistinguishability – for the two-photon amplitudes from i1 and i2, hence leading to zero coincidence counts at zero delay ($CC_{i2,i1|s1}(0) = 0$). In contrast, the three-fold events from multiphoton components in the heralded state i1 were presumed to remain intact as a result of emerging from two photons in the same frequency mode, i.e., perceived as background terms. On this account, a minimum predicted value $CC_{pr}(0) = CC_{i1,i1|s1}(0) \sim 485\pm40$ was foreseen for the non-delayed coincidence counts – considering the enhancement coefficient. However, in experiment $CC(0) = 411\pm20$ was measured which falls outside the standard deviation range and below the minimum predicted amount $CC_{pr}(0)$. Importantly, as conducted in previous works [22] subtraction of $CC_{i1,i1|s1}(0)$ from $CC(0)$ – if assumed as background – would lead to negative values, hence proved unphysical. The difference between experiment and initial expectation is explainable by engagement of heralded state multiphoton components in the HOM effect with the thermal field. This is verified by the theory derived in equation (3) and illustrated in **FIG. 4** showing the dependency of the HOM visibility on $\bar{n}_{i2}$ and $\bar{n}_{i1,th}$. The dashed arrow shows the conjunction between $\bar{n}_{i2}$ and $\bar{n}_{i1,th}$ from experiment and the corresponding visibility. Under $\bar{n}_{i2} \ll 1$ and for $\bar{n}_{i1,th} = 0$, 100% visibility is achievable. For increasing values of $\bar{n}_{i1,th}$, the visibility decreases as a consequence of multiphoton components added to mode i1 (i.e., under the emergence of an imbalance between the thermal mean photon numbers), which leads to coincidence counts at zero-delay, hence a reduction in visibility. However, with increasing $\bar{n}_{i2}$, the imbalance between $\bar{n}_{i1,th}$ and $\bar{n}_{i2}$ is reduced, yielding an improvement in the visibility. The interplay between the thermal fields indicates the engagement of multiphoton components of the heralded state in the quantum interference.

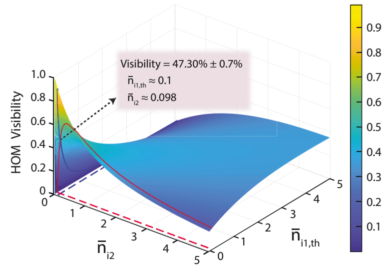

FIG. 4. Visibility of the HOM interference between a thermal field and a heralded state, as function of average photon number per pulse period of the thermal field ($\bar{n}_{i2}$) and the thermal part of the heralded state ($\bar{n}_{i1,th}$). The dashed arrow points to the intersection of the experimentally measured mean photon numbers $\bar{n}_{i1,th} \approx 0.1$ and $\bar{n}_{i2} \approx 0.098$, in turn corresponding to the theoretical value of the HOM visibility $V_{theory} \approx 47.3\% \pm 0.7\%$.

Our approach allows to determine the nonclassicality degree of a heralded state [32] which depends on the average photon number of its multiphoton components. A negative Mandel parameter ($Q_M < 0$) is sufficient to classify a field as nonclassical [31,33,34]. For a heralded state $Q_M = (\bar{n}^2_{i1,th} - 1)/(\bar{n}_{i1,th} + 1)$, from which we derive an upper bound on the average photon number of its multiphoton components $\bar{n}_{i1,th} < 1$ to realize nonclassicality. This condition corresponds to a lower bound on the peak visibility of the heralded state's HOM effect with a thermal field, such that for visibilities $V > 41.42\%$ the heralded state can be classified as nonclassical. As depicted in **FIG. 5**, HOM visibility varies with the average photon number $\bar{n}_{i2}$ of a thermal field. Two cases are presented: HOM between a heralded state and a thermal field (solid curves) and HOM between two thermal fields (dashed curves). The solid curves follow equation (3), whereas the dashed curves are based on the equation in **Appendix I**. In the case of HOM between two thermal fields, the maximum visibility reaches approximately 33.33%.

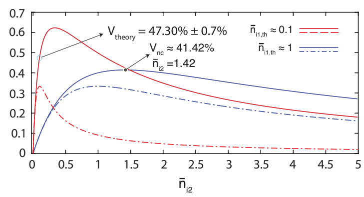

FIG. 5. HOM visibility versus $\bar{n}_{i2}$ for fixed values of $\bar{n}_{i1,th} = 0.1$ and $\bar{n}_{i1,th} = 1$, corresponding to the experimental value and the nonclassicality upper threshold of the multiphoton components in the heralded state. The $V_{theory} \approx 47.3\% \pm 0.7\%$ is our theoretical HOM visibility under $\bar{n}_{1,th} \approx 0.1$ and $\bar{n}_2 \approx 0.098$.

For two thermal fields in i1 and i2 (see **Appendix I & J**), realized by discarding heralding detections on D3, the theoretical $V_{theory} \approx 33.32\%$ and experimental $V_{exp} = 28.4\% \pm 3.1\%$ visibilities were obtained that fell below the upper limit of $\sim 33.33\%$ [35] set for the HOM effect between two thermal fields, hence affirming the validity of our approach and analysis. While photon number resolving detectors could enhance heralded state statistical characterization, their limited detection efficiencies and substantial timing jitters hinder their adoption in quantum photonic labs [36]. Our results provide insights into the HOM effect and propose using controlled higher intensities of heralded states for MDI-QKD protocols, which can improve the key-rate, speed up the process, and reduce statistical fluctuations in information processing.

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