Wigner Function and Photon Statistics - Photon Indistinguishability and Quantum Interference

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Abstract

In this report, we explore the Wigner quasiprobability distribution and its role in quantum optics, focusing on the measurement of subpicosecond time intervals between two photons through the Hong-Ou-Mandel (HOM) interference effect. Key topics include photon indistinguishability, quantum interference effects and photon statistics. We review foundational experiments by Hong, Ou, and Mandel (1987) and recent advances in photon imaging technologies.

1 Introduction

Photon statistics and the Wigner function play a crucial role in understanding non-classical light. The Wigner function serves as a phase-space distribution function, providing insights into quantum states where classical analogs fail. Photons, obeying Bosonic statistics, exhibit unique quantum behaviors such as bunching and anti-bunching, which are pivotal for technologies like quantum computing and secure communication. We will explore the theory of the Wigner Function and Photon statistics, and then we will review the original Hong-Ou-Mandel 1987 paper, and the new 2015 rendition by Michał Jachura and Radosław Chrapkiewicz that includes higher precision and spatial resolution of photon coalescense.

2 Theory

2.1 Wigner Function

The Wigner function, introduced by Wigner in 1932, is a quasiprobability distribution used in quantum mechanics to represent quantum states in phase space. Due to the Heisenberg uncertainty principle, points in phase space are not well-defined as in the classical phase space, requiring the use of regions. Think of it as an region of area $A = \Delta x \Delta p = \hbar^2/4$. The general Wigner distribution for a mixed state described by the density operator $\hat{\rho}$ is given by:

$$W(x,p) \equiv \frac{1}{2\pi} \int_{-\infty}^{\infty} dx \left\langle q - \frac{x}{2} \middle| \hat{\rho} \middle| q + \frac{x}{2} \right\rangle \exp(ipx) \tag{1}$$

For Fock states $|n\rangle$, the Wigner function becomes:

$$W_{|n\rangle}(\alpha) = \frac{2}{\pi}(-1)^n e^{-2|\alpha|^2} L_n(4|\alpha|^2) \tag{2}$$

where L_n are Laguerre polynomials. The Wigner function of the first four Fock states have been shown in Fig. (1). It results in a very non-intuitive result that has no classical analog. For the Fock state $|0\rangle$, meaning there is no light present, we still measure fluctuations with variance $\hbar^2/4$. The Wigner function becomes

$$W_{|0\rangle}(\alpha) = \frac{2}{\pi} e^{-2|\alpha|^2} \tag{3}$$

Having a maxima at the origin and exponentially decaying out in phase space. This is precisely the "vacuum states", and have been demonstrated to be fluctuations in the quantum vacuum or quantum fluctuations, resulting in physical phenomena like the Casimir effect [ref]. We are going to get a signal despite the having no photons in our system, which sets our "standard quantum limit". Consider now a single excitation $|1\rangle$

$$W_{|1\rangle}(\alpha) = -\frac{2}{\pi} e^{-2|\alpha|^2}(1 - 4|\alpha|^2) \tag{4}$$

This is not expected. We have a negative probability for a single photon state in the quadrature distribution. The minima is the origin, corresponding to having zero probability of being at the origin of phase space. This means that whenever we measure a single photon state, we will measure a random number and value, but very unlikely $(0, 0)$ in phase space. It's important to understand from this result that this causes us to never actually measure a

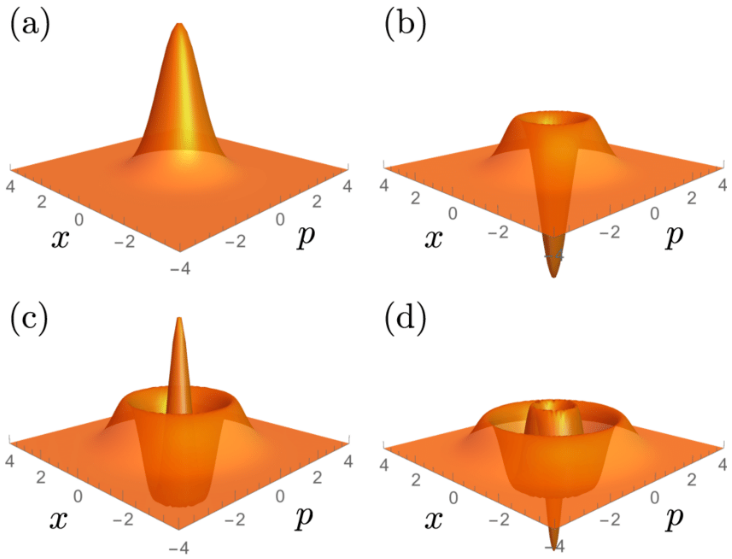

Figure 1: The Wigner Function of the first four Fock States a) $|0\rangle$, b) $|1\rangle$, c) $|2\rangle$, d) $|3\rangle$

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single photon in experiments, because we always have some probability of losing it on the way to the detector from the source. We instead get a mix of single photon and the vacuum fluctuations, resulting in sort of a small dip in the Gaussian of the single photon.

It is apparent in Fig. [1] that the probability is always highest for even numbers. What does this mean? Well that it's only possible for us to only observe identical/indistinguishable photons in pairs. This is precisely shown as the key result in the papers we will be reviewing about the *Hong-Ou-Mandel interference.* It can also explain that photons experience bunching and anti-bunching and that quantum entanglement is possible, due to the innate photon statistics.

Therefore, in experiments, the output port will always only detect the photons in pairs if they are indistinguishable. Only when the modes are distinguishable, we will detect singular photons. In other words, distinguishable particles can only be observed in a "lonely" state. A more detailed reasoning by looking at the output states and probabilities is crucial to see how the different photon states cancel out due to destructive interference.

2.2 Coherent States in Fock Space

Looking at Quantum states of light and coherent states, it is quite different than the classical intuition. Schrödinger and Glauber were looking for what was the most "classical" state, thinking it should somehow reduce to a laser or a light field. The coherent state is the closest analog to the classical version that incorporates Heisenbergs uncertainty principle. It is important to note that a coherent state is not a pure photon state, it is a mixture of photons, a superposition of Fock states/photons $|n\rangle$ that minimizes the uncertainty in the form of

$$|\alpha\rangle = e^{-|\alpha|^2/2} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle \, , \quad |n\rangle \in F_\nu(H) = \bigoplus_{n=0}^{\infty} S_\nu H^{\otimes n} \tag{5}$$

It is the most classical state, with an amplitude of the intensity of the electric field $\alpha \propto E \implies |\alpha|^2 \propto I$. In the Wigner distribution, the coherent states are equivalent to just displacing the vacuum state, showing the connection between their statistics. So the state $|\alpha = 2\rangle = D(\alpha = 2) |0\rangle$, where $D(\alpha) = e^{\alpha a^\dagger - \alpha^* a}$ is the displacement operator. The only difference being then is that it is like a sine wave, but with "vacuum fuzz", which is demonstrated in Fig. [2]

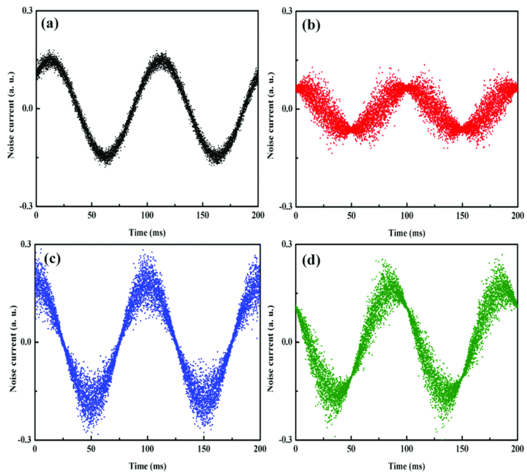

Figure 2: Noise distribution of the generated squeezed states. (a) Coherent state. (b) Amplitude-squeezed state. (c) Phase-squeezed state. (d) Squeezed state with a squeezing angle of /3. 4 Yinghao et al. "Generation of stable, squeezed vacuum states at audio frequency using optical serrodyne sideband modulation locking method". Laser Physics Letters (2019).

2.3 Propagation of the optical field in the Heisenberg picture

To understand how to quantized EM field behaves in a time evolution, we consider the Heisenberg picture, where the statevectors are static and the operators evolve in time. For a given system Hamiltonian $\hat{H}$ and some arbitrary operator $\hat{O}$, we have the Heisenberg picture given as

$$\frac{d}{dt}\hat{O}(t) = \frac{1}{\hbar}[\hat{H}, \hat{O}(t)] \tag{6}$$

where the total Hamiltonian of the optical field is

$$\hat{H} = \sum_k \hbar\omega_k a^\dagger(k)\hat{a}(k) \tag{7}$$

Such that the time evolution of the annihilation operator is accordingly

$$\begin{aligned}
\frac{d}{dt}\hat{a}(\mathbf{k},t) &= \frac{1}{\hbar}[\hat{H}, \hat{a}(k,t)] = \frac{1}{\hbar}[\hbar\omega_k\hat{a}^\dagger\hat{a}, \hat{a}] = i\omega_k\hat{a}(\mathbf{k},t) \\
\frac{d}{dt}\hat{a}(k,t) &= i\omega_k\hat{a}(\mathbf{k},t) \implies \hat{a}(\mathbf{k},t) = \hat{a}_0(\mathbf{k}) \cdot e^{-i\omega_k t}
\end{aligned}$$

Such that the time dependent quantized EM field becomes

$$\hat{E}(\mathbf{r},t) = i\sqrt{\frac{\hbar\omega}{2\epsilon_0 V}}\left(\hat{a}(\mathbf{k},t)e^{i\mathbf{k}\cdot\mathbf{r}} - \hat{a}^\dagger(\mathbf{k},t)e^{-i\mathbf{k}\cdot\mathbf{r}}\right) = \hat{E}^{(+)}(\mathbf{r}) + \hat{E}^{(-)}(\mathbf{r}) \tag{8}$$

2.4 Hong-Ou-Mandel Interference

Now to understand how the output states ends up with only photons in pairs for indistinguishable photons, it is important to investigate the Hong-Ou-Mandel (HOM) interference. HOM interference is a quantum optical phenomenon demonstrating the indistinguishability of photons. Two indistinguishable photons incident on a beam splitter exit together due to quantum interference, leading to zero coincidence counts at detectors [1]. This effect is described by the transformation of input photon states at a perfect 50:50 beam splitter:

$$|1_1\rangle\,|1_2\rangle \to \frac{1}{\sqrt{2}}(|2_1, 0_2\rangle - |0_1, 2_2\rangle) \tag{9}$$

This state shows no coincidence detections, implying perfect destructive interference for indistinguishable photons, although with always some small error in experiments.

You will only observe two photons in mode 1 or two photons in mode 2, never by themselves if they are perfectly indistinguishable. The output state is similarly

$$|\psi_{out}\rangle = (R-T)|1_1, 1_2\rangle + i(2RT)^{1/2}|2_1, 0_2\rangle + i(2RT)^{1/2}|0_1, 2_2\rangle \tag{10}$$

If we look back at the coherent states that we discussed earlier, the classical analogue to the HOM effect occurs for two coherent states (in practice laser beams) that interfere at a beam splitter. If there is a big difference in phase, we will observe a coincidence rate that is equal to half of the average count at long delays $c\delta\tau$. We can introduce delay to increase coincidence counts. If $R+T=1$, then we have that the displacement of the beam splitter appears as a delay in the field expression at the detectors as

$$\hat{E}_1^{(+)}(t) = \sqrt{T}\hat{E}_{01}^{(+)}(t-\tau_1) + i\sqrt{R}\hat{E}_{02}^{(+)}(t-\tau_1+\delta\tau) \tag{11}$$

$$\hat{E}_2^{(+)}(t) = \sqrt{T}\hat{E}_{02}^{(+)}(t-\tau_1) + i\sqrt{R}\hat{E}_{01}^{(+)}(t-\tau_1-\delta\tau) \tag{12}$$

where τ_1 is the propagation time from mirror to detector, and $\pm c\delta\tau$ is the small displacement of the BS towards on or the other detector. We should register close to zero coincidences as the delay goes approaches zero. Recall the definition in the theory that the time dependence was for the annihilation operator in the Heisenberg picture. Therefore, the displacement of the beam splitter introduces a delay in the phase of the annihilation of a photon with

$$\hat{a}(k, t = t-\tau_1 \pm \delta\tau) = \hat{a}_0(k)e^{-i\omega(t-\tau_1\pm\delta\tau)} \tag{13}$$

As the delay between the idler and signal photons to the detectors become smaller and smaller, the coincidence count get steeper and goes towards a minima (optimally to zero). This is explained as where the fields destructively interfere, and we have a pair of indistinguishable photons!

The basic entangling mechanics in linear optical quantum computing in typical $NOON$ states are explained by the HOM effect as the two-photon quantum state $|2,0\rangle + |0,2\rangle$ as seen above. Several experimental results observe this with the HOM-dip, which is characteristic for experiments involving the HOM effect as in Fig. [5]. We plot the number of coincidence counts versus their delay or position of beam splitter by $c\delta\tau$.

How well we see the HOM-dip is dependent of the visibility of the HOM interference. The visibility of the interference is related to the states of the two photons ρ_a, ρ_b as

$$V = Tr(\rho_a\rho_b) \tag{14}$$

For indistinguishable photons $\rho_a = \rho_b = \rho$, it is simply the purity of the source $P = Tr(\rho^2)$. An optimal single-photon source should deterministically deliver one photon at a time with no trade-off between photon indistinguishability and efficiency of source.

One way to empirically observe the HOM-effect was firstly by Hong, Ou and Mandel in 1987 by spontaneous parametric down conversion (SPDC) with a nonlinear crystal and a 50/50 beamsplitter. It showed the characteristic dip down to almost zero coincidences (except accidentals due to experimental limitations) as seen in Fig. [5].

Almost 30 years later in 2015 it was observed by Michal and Radoslaw, using single-photon-senstive intensified "sCMOS" cameras that registered single photons as bright spots. The bright spots are clearly distinguished from the low-noise background or the quantum fluctuations as seen in Fig. [4].

2.5 Photon statistics in HOM dip measurements

Consider the Fourier transform of the weight function $\phi(\omega_1, \omega_2)$

$$G(\tau) = \int d\omega \phi(\omega_0/2 + \omega, w_0/2 - \omega) e^{-i\omega t} \tag{15}$$

As a source ω goes through SPDC in a nonlinear crystal, we get through energy conservation two beams with lower energy ω_1, ω_2, equivalent to the fact that $\omega_0 = \omega_1 + \omega_2$. This is a idler and a signal photon. The corresponsing correlated two-photon state is defined as

$$|\psi\rangle = \int d\omega \phi(\omega_1, \omega_0 - \omega_1) |\omega_1, \omega_0 - \omega_1\rangle \tag{16}$$

They also have a joint probability distribution of the detection of photons at both detectors at times t and $t + \tau$ given as

$$P_{12}(\tau) = K|G(0)|^2 \left[T^2|g(\tau)|^2 + R^2|(g(2\delta\tau - \tau)|^2 - RT(g^*(\tau)g(2\delta\tau - \tau) + c.c.)\right] \tag{17}$$

If the variables were independent, the two-photon states would be possible to be split up into a product of two single photon states. During HOM interference, they cannot be separated into a product of two single photon states since the DC photons are entangled, thus their frequency are dependent on each other. The photons are indistinguishable and they have spectral-temportal dependencies. This further showcases the fundamentally non-classical behavior of the photon statistics. To prove that the destructive interference is a two photon quantum interference, we impose that the number of coincidence count N_c **must** be lower than one half, as in the classical analog.

The expected number N_c of photon coincidences is given by

$$N_c = C\left[R^2 + T^2 - 2RT\frac{\int_{-\infty}^{\infty} g(\tau)g(\tau - 2\delta\tau)d\tau}{\int_{-\infty}^{\infty} g^2(\tau)d\tau}\right] \tag{18}$$

and in the special case when the correlation function $g(\omega_0/2 + \omega, \omega_0/2 - \omega)$ is Gaussian in ω with some bandwidth $\Delta\omega$, we get that $g(\tau) = e^{-(\Delta\omega\tau)^2/2}$, such that it simplifies to

$$N_c = C(R^2 + T^2)\left[1 - \frac{2RT}{R^2 + T^2}g(\tau)\right] \tag{19}$$

These curves will be superposed with the experimental data in the next section. We can already see that for a 50/50 beamsplitter with $R = T = 1/2$, and zero delay between photon arrival time $\tau \to 0$, we get zero photon coincidences, $N_c \to 0$. This corresponds to having an indistinguishable photon pair. It is closely tied to the sub-Poissonian statistics of the photon source, typical of single-photon Fock states with photon number variance being lower than a classical Poisson distribution for coherent states.

Photon statistics are characterized by the second-order correlation function $g^{(2)}(0)$, which describes photon bunching or anti-bunching. The HOM effect relies on **anti-bunched light**, where $g^{(2)}(0) = 0$, meaning photons tend not to arrive simultaneously in the same mode. For classical (bunched) light with $g^{(2)}(0) > 1$ (as in a thermal or coherent state), photon bunching reduces the quantum interference, leading to a higher coincidence rate and lower visibility in the HOM experiment.

3 Experimental Review

3.1 Measurement of Subpicosecond Intervals

Hong, Ou, and Mandel's 1987 experiment measured subpicosecond time intervals using two-photon interference. The setup involved a 50:50 beam splitter and two single-photon detectors. The temporal overlap of photons led to a reduction in coincidence counts, forming a "dip" that provides temporal resolution down to femtosecond scales.

The experiment is **physically measuring photon coincidence rate** between the two detectors placed at the output ports of the 50:50 beam splitter, which is sensitive to temporal overlap of two photons generated from the SPDC source. The measurement reveals that the two photons are indistinguishable when the coincidence rate drops to a minima (or near zero). The decrease in coincidence rate is equivalent to destructive interference of the wavepackets, indicating temportal overlap and directly providing insight to the coherent time t_c of the photons.

3.2 Recent Advances in Photon Imaging

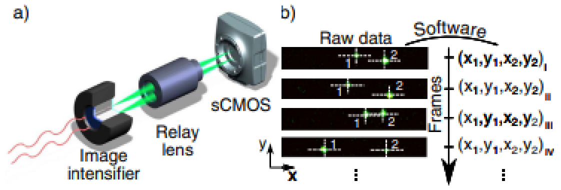

Fig. 1. (a) Scheme of the intensified sCMOS camera detection system. (b) Single-photon detection seen as bright phosphore flashes are localized with a subpixel resolution using the real-time processing software algorithm. We preselect events where at least two photons are detected.

Figure 3: (a) Scheme of the intensified sCMOS camera detection system. (b) Single-photon detection seen as bright phosphore flashes are localized with a subpixel resolution using the real-time processing software algorithm. We preselect events where at least two photons are detected. Michał et al. Shot-by-shot imaging of Hong–Ou–Mandel interference with an intensified sCMOS camera *Optics Letters (2015)*

Jachura and Chrapkiewicz (2015) demonstrated shot-by-shot imaging of HOM interference using an intensified sCMOS camera, allowing for spatially resolved detection of photon pairs. Their work significantly advanced the resolution of quantum optical experiments and paved the way for more precise photon measurements. This experiment **physically measures** two-photon coincidence rate, but as an extension of the classical 1987, also includes spatial resolution as a physical measurement. This helps visualize the coalescense of photons only being detected in one singular port if they are indistinguishable, otherwise the distiguishable photons stay lonely and not in pairs, as seen in figure [4]. When the photons are identical their wavefunctions interfere such that the states corresponding to "neither photon pairs up" and "both photons pair up (i.e they swap places)" destructively cancel. Think of it like this: if the photons are identical, the first state is the same as the second state, just with a negative sign, so they have to cancel and the only

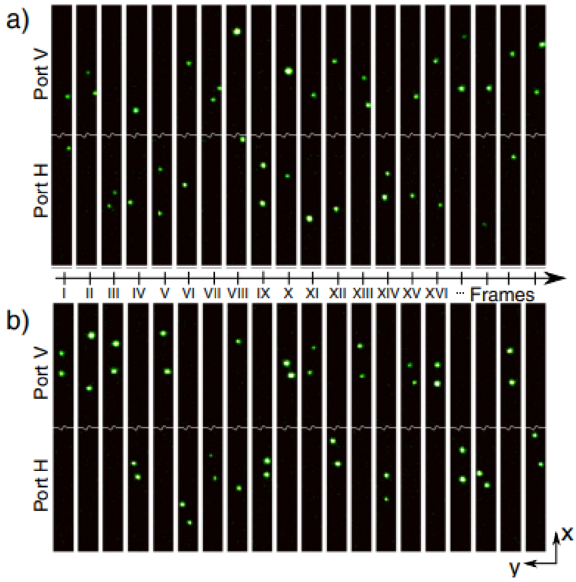

Figure 4: 20 frames from co-incidences on H and V port of a beamsplitter for **a)** distinguishable photons and **b)** indistinguishable photons. Michał et al. Shot-by-shot imaging of Hong–Ou–Mandel interference with an intensified sCMOS camera *Optics Letters (2015)*

states left are where one photon pairs up.

Being distinguishable is the same as being lonely in the quantum world, whereas indistinguishable you pair up with another identical photon. A stream of photons will have some statistics depending on the source and whats been done to them prior to detection. If the photons are closer together than they would be if they obeyed Poissonian statistics, they are bunched. Basically, if two indistinguishable photons enter different input ports of a beam-splitter, they will always exit the same port together. This is precisely what is shown by the green dots on **b**) in Fig. [5] and is always the case if they are highly indistinguishable. It can only be explained by the fact that there is destructive interference happening.

4 Discussion

. We imposed earlier that the number of coincidence count N_c **must** be lower than one half, which is clear from Fig. [5]. HOM interference provides direct evidence of photon indistinguishability and destructive quantum interference. The recent technological advances as we see in the second curve in Fig. [5] is close to perfect, having a visibility of $V = 96.3 \pm 1.1\%$, including intensified

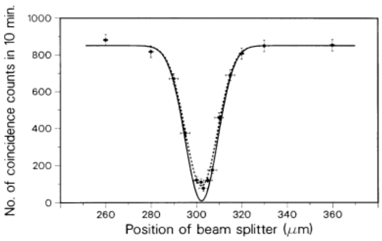

FIG. 2. The measured number of coincidences as a function of beam-splitter displacement $c\delta\tau$, superimposed on the solid theoretical curve derived from Eq. (11) with $R/T=0.95$, $\Delta\omega=3\times10^{13}$ rad s^{-1}. For the dashed curve the factor $2RT/(R^2+T^2)$ in Eq. (11) was multiplied by 0.9. The vertical error bars correspond to one standard deviation, whereas horizontal error bars are based on estimates of the measurement accuracy.

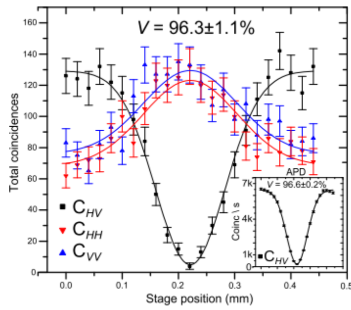

Fig. 4. Recovery of the HOM-dip from the coincidences between ports C_{HV} measured by means of a camera system along with photon pairs detected at single output ports C_{HH}, C_{VV}. Inset: the analogous result C_{HV} obtained using the avalanche photo diodes setup.

Figure 5: If the delay / beam splitter position $c\delta\tau$ between them is large, we can register some average number of coincidence count. In this case, the two wavepackets in the different modes are distiguishable and theres no interference taking place. If the delay becomes smaller and smalles, the wavepackets begin to overlap and destructively interfere, meaning we register close to zero coincidence count, causing the HOM dip curvature. At zero delay the photons arrive at the same time, ideally causing zero coincidence and a stronger interference visibility.

cameras, allow for more refined measurements and contribute to the growing field of quantum imaging [2].

To see it from a more applied perspective, the HOM effect proves itself a powerful tool for example for implementing two-qubit gates in linear optical quantum computing. The HOM interference is utilized with indistinguishable photons at beam splitters to perform quantum logic like the typical CNOT or CZ gates. It is however important to note that these gates are probabilistic as discussed earlier, and require high precision to be scalable.

4.1 Physical limitations

Temporal, spectral and spatial distinguishability between the DC signal and idler photon significantly reduces the interference visibility. All degrees of freedom must be indistinguishable for the two photons for the interference to be occur. In the 1987 paper, Hong et. al. mention the need for high overlap between the photon wavepackets in the temporal domain. Temporal mismatch reduces overlap and thus visibility.

Firstly, **photon flux rate** causes accidental co-incidences and multi-photon emissions, which in turn lowers interference visibility. When two photons from independent pairs get accidentally detected as coincident, they can quadratically increase accidentals with the gating time of the detection system. The newer system from 2015 with the sCMOS camera, uses a carefully adjusted gating time (here 40 ns) to mitigate the accidentals.

Furthermore, the **detector resolution** implies that poor detector timing resolution simply blurs the temporal correlation between photons. Resolution should be much smaller than the coherence time of the photons. If the detector timing jitter is large relative to the photon coherence time, the temporal overlap of the photons will not be measured accurately, reducing the sharpness of the HOM dip.

Next we must consider **detector noise** and **dark counts**. The 2015 paper acknowledges this issue and emphasizes that a "high signal-to-noise" ratio is crucial for good visibility (2). The way they minimized dark counts was precisely by using advanced photon detectors like the intensified sCMOS camera that is specifically designed for low noise at single-photon level.

Other issues are certainly quantum fluctuations, beam splitter imperfections, optical misalignment and filter bandwidth. The 1987 paper discusses non-ideal beam splitters to be perfectly ideal 50:50 beam splitters for perfect destructive interference. They accounted for a reflectivity/transmissivity ratio of 0.95, leading to small residual coincidences at the dip (1). The residuals could also possibly be affected by quantum fluctuations.

Optical misalignment such as mirrors or apertures can impose imperfect overlaps between the two DC signal and idler photon modes. Lastly, the filter bandwidth in the detection paths does ultimately determine the coherence time. If the bandwidth is too large, the frequency correlation between photons become inconsistent, reducing the visibility.

It is clear that the Michal et. al. (2015) sCMOS camera technique substantially increased the visibility up to $V = 96.3 \pm 1.1\%$, which means that high intensity cameras like the sCMOS is a promising technology to address these issues as well as other techniques like optical delay lines and a more advanced experimental setup.

4.2 Width of the dip $\delta\tau$ feature in coincidence measurement and spatial coherence length

If the delay between them is large, we can register some average number of coincidence count. In this case, the two wavepackets in the different modes are distiguishable and theres no interference taking place. If the delay becomes smaller and smalles, the wavepackets begin to overlap and destructively interfere, meaning we register close to zero coincidence count - causing the HOM dip curvature - at zero delay the photons arrive at the same time -¿ ideally causing zero coincidence Is it consistent with the spatial coherence length? Well for a single photon, the original experiment showed $t_c = 32\mu m = 100fs$. The HOM dip width reflects the temporal overlap of **two-photon** interference, which is precisely **half** the coherence length of each individual photon, hence $\delta\tau = 16\mu m = 50fs$. This is consistent with the spatial coherence length.

The spatial coherence extent is the range over which the optical pulse can keep a consistent phase relationship $L_c = \frac{\lambda_o^2}{\Delta\lambda}$. Depends in practice on size of laser and wavelength, here 351.1 nm argon-ion laser.
Spatial coherence extent can be determined from the bandwidth of the IF filters and the central wavelength of the photons. Narrower bandwidth $\Delta\lambda$ implies longer coherence length. We assume that the direction of signal & idler photons are well defined by the aperture, but frequency spreads are substantial, which is largely determined by the interference filters IF)

When an optical pulse passes through an interference filter, spatial filtering can occur. The filter can allow only certain spatial modes of the light to propagate, effectively selecting regions of coherence.

So the question remains, which element enables precise tuning of delay between pulses? Since the HOM dip is related to coherence time of photon wave packets, the detector timing must be finer than the coherence time. Hong, Ou and Mandel were using a precisely calibrated micrometer, with potential improvements by utilizing piezoelectric transducers. One of the more recent techniques that Michal et. al. employs were optical delay lines. In the Hong-Ou-Mandel (HOM) interference experiment, precise tuning of the delay between the two optical pulses (i.e., the two down-converted photons) is crucial for observing the interference effect. This delay controls the temporal overlap of the two photons at the beam splitter. If the photons arrive at the beam splitter at exactly the same time, they will destructively interfere, and reduce coincidence counts, leading to the HOM dip.

5 Conclusion

With the Hong-Ou-Mandel effect, we are able to measure subpicosecond time intervals between two photons. The study of photon statistics and the Wigner function is essential for understanding these non-classical and non intuitive results in quantum optics. The Wigner function's negativity in certain regions highlights the non-classical nature of quantum states and the interference that we see in the HOM dip, which contrasts with classical phase space distributions. The effect is readily used in methods like linear optical quantum computing for performing essential quantum logic gates with high precision. There are also potential improvements that would make the technique more powerful, with intensified cameras as the most promising technologies as demonstrated by Michal et. al.

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