Photon Statistics and Heralded Single Photons

Quantum Information Laboratory Report

Chanseung Lee and Yongmin Kwon
Department of Applied Physics, Kyung Hee University | 7 November 2025

Abstract

We compared photon statistics using Hanbury Brown–Twiss (HBT) and Grangier–Roger–Aspect (GRA) measurements of attenuated laser light, spontaneous parametric down-conversion (SPDC), and a fluorescent reference. The laser and unheralded SPDC arm gave correlations near unity, while the SPDC inter-arm correlation was 138.9889. Heralding reduced the conditional correlation to 0.016426 ± 0.000153 for 20 s acquisitions, with the uncertainty reported as the standard deviation across ten measurements. The fluorescent reference remained near unity. These results support heralded single-photon operation and distinguish photon-pair correlations from conditional single-photon statistics.

1 Physical background

1.1 Second order correlation

The normalized second-order correlation measures the likelihood of joint detections separated by delay τ. For a stationary classical field it is $\langle I(t)I(t+\tau)\rangle/\langle I(t)\rangle^2$. For a quantum field, the normally ordered expression is

$$g^{(2)}(\tau) = \frac{\langle a^\dagger(t)a^\dagger(t+\tau)a(t+\tau)a(t)\rangle}{\langle a^\dagger(t)a(t)\rangle^2} \quad (1)$$

Here a and a† are bosonic annihilation and creation operators, and angle brackets denote an ensemble or time average. With n = a†a and [a, a†] = 1, the zero-delay correlation becomes

$$g^{(2)}(0) = \frac{\langle n(n-1)\rangle}{\langle n\rangle^2} = 1 + \frac{Var(n) - \langle n\rangle}{\langle n\rangle^2} \quad (2)$$

1.2 Photon statistics and detector resolution

A coherent state obeys $a|\alpha\rangle = \alpha|\alpha\rangle$ and has Poissonian statistics: $\langle n\rangle = Var(n) = |\alpha|^2$, so $g^{(2)}(0) = 1$. Attenuation lowers the mean photon number but does not remove the multiphoton component. An ideal single-mode thermal state has $Var(n) = \langle n\rangle^2 + \langle n\rangle$ and $g^{(2)}(0) = 2$. In this kit, however, the coincidence window is much longer than the optical coherence time, so unresolved bunching can yield a measured correlation near unity [1].

An ideal one-photon Fock state has $g^{(2)}(0) = 0$. A small measured value indicates suppressed multiphoton events, but does not alone quantify the vacuum contribution, heralding efficiency, or complete state purity. A value near unity likewise does not establish that the source is coherent.

1.3 SPDC in a BBO crystal

In beta-barium borate (BBO), SPDC converts a pump photon into signal and idler photons. Energy conservation and phase matching require

$$\omega_p = \omega_s + \omega_i; \quad k_p = k_s + k_i \quad (3)$$

The subscripts denote pump, signal, and idler, and k denotes a wave vector. BBO birefringence permits phase matching for a 405 nm pump and photons near 810 nm. The kit uses a nominal cut angle of 29.2° and a 3° emission-cone half-angle [1]. Detecting one partner provides the herald for analysis of the other.

2 Experimental configurations

Five configurations were compared using the Thorlabs quantum optics kit. T denotes the partner or herald channel; A and B denote the outputs of the analyzed arm. Figures 1–5 reproduce the setup schematics used in the laboratory report, from the kit guide [1, Sections 9.1–9.5].

2.1 Attenuated laser HBT

The alignment laser passed through a neutral-density filter and a beam splitter. Detectors A and B measured singles and coincidences. Ten 20 s acquisitions provided the laser reference.

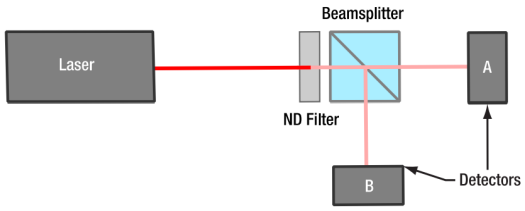

Figure 1. HBT measurement of the attenuated laser.

2.2 Photon pair correlation

The pump illuminated the BBO crystal. Detectors T and A collected opposite SPDC arms, and their singles and coincidence rates were used to evaluate the inter-arm correlation over ten measurements.

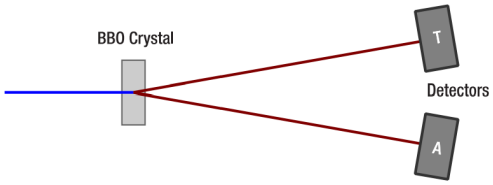

Figure 2. Collection of correlated SPDC arms.

2.3 Unheralded SPDC arm

A beam splitter directed one SPDC arm to A and B. The path to T was blocked, and ten A–B correlation measurements were recorded without heralding.

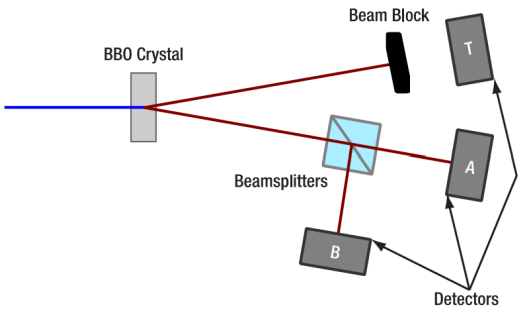

Figure 3. HBT configuration with the T arm blocked.

2.4 Heralded SPDC in the GRA setup

The T-arm block was removed, and A–B statistics were conditioned on detections at T. Ten acquisitions were recorded at each of 1 s and 20 s to compare the conditional mean and repeatability.

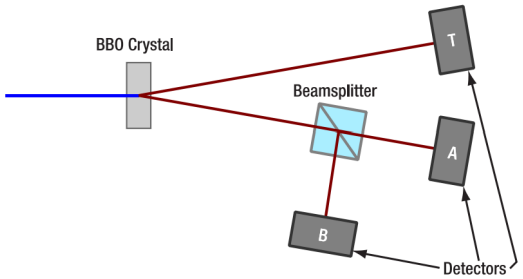

Figure 4. GRA measurement with detector T as herald.

2.5 Fluorescent reference

The BBO crystal was replaced with a fluorescent filter, retaining the three-detector arrangement. Ten measurements provided a classical reference without the SPDC pair correlations.

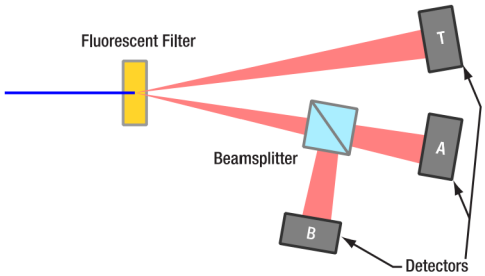

Figure 5. GRA measurement with fluorescent light.

Acquisition conditions

The guide prescribes 20 s for laser HBT, 10 s for unheralded HBT and fluorescence, and 1 s plus 10 s for GRA [1, pp. 106–110]. Our GRA series used 1 s and 20 s; the unheralded and fluorescent example screens also show 20 s. Protocol durations are therefore distinguished from the recorded acquisitions.

The pair-source protocol uses count rates without a fixed acquisition duration. The GRA rate record notes 35 mW laser power. Acquisition duration, coincidence window Δt, and optical delay τ are distinct quantities.

3 Correlation analysis and results

HBT and inter-arm correlations were evaluated from singles and twofold coincidence rates. With R denoting counts per unit time and Δt the coincidence window, the kit uses [1]

$$g^{(2)}{}_{HBT}(0) = \frac{R_{AB}}{R_A R_B \Delta t}; \quad g^{(2)}{}_{PS}(0) = \frac{R_{TA}}{R_T R_A \Delta t} \quad (4)$$

The GRA correlation conditions the A–B measurement on detection at T. For counts collected during the same acquisition interval,

$$g^{(2)}{}_{h}(0) = \frac{N_{TAB} N_T}{N_{TA} N_{TB}} \quad (5)$$

Here N_T denotes herald counts, N_{TA} and N_{TB} twofold coincidences, and N_{TAB} threefold coincidences. Coincidence counts must use a consistent timing convention [1, 2]. Table 1 preserves all reported means and standard deviations; each condition comprises ten measurements.

Table 1. Measured correlations. Standard deviations describe repeat-to-repeat scatter, not standard errors.

Configuration	Mean correlation	Standard deviation
Attenuated laser HBT	1.045	0.06
SPDC inter-arm pair correlation	138.9889	0.297203
Unheralded SPDC arm HBT	1.003554	0.054255
Heralded SPDC GRA at 1 s	0.016047	0.005796
Heralded SPDC GRA at 20 s	0.016426	0.000153
Fluorescent reference GRA	0.999589	0.009825

3.1 Laser reference and pair generation

The laser HBT mean of 1.045 is close to unity relative to its reported scatter of 0.06, consistent with Poissonian statistics (Figure 6). The SPDC inter-arm mean of 138.9889 indicates a strong excess of coincidences over the uncorrelated baseline. This large finite correlation supports pair generation; it is a different observable from the conditional single-arm correlation.

3.2 The role of heralding

The unheralded A–B mean of 1.003554 is compatible with thermal statistics whose bunching is unresolved by the measurement system (Figure 8). Blocking T removes the heralding information used in the analysis, without changing the unconditional source statistics.

With heralding enabled, the means fell to 0.016047 at 1 s and 0.016426 at 20 s. Both show strong suppression of threefold coincidences and support heralded single-photon operation (Figures 9 and 10). The means are similar, while the reported scatter is smaller for the longer acquisition.

3.3 Classical control

The fluorescent reference yielded 0.999589, with no comparable coincidence suppression (Figure 11). The guide describes the emission as thermal light with uncorrelated herald and signal events [1, Section 9.5]. Its measured correlation near unity is therefore a classical control, rather than evidence of a coherent state.

4 Measurement quality and interpretation

4.1 Alignment and background

Lower-than-anticipated count rates suggest a need to improve collection and alignment, but do not isolate a single cause. Optical losses, detector response, collection efficiency, and background conditions can all affect singles and coincidence rates. Alignment should therefore be assessed using true coincidence rates as well as singles, with the two collection paths adjusted symmetrically around the SPDC cone.

Blocked-path measurements would quantify detector dark counts and ambient-light background. Rechecking channel delays and the coincidence window would help separate genuine pairs from accidental coincidences. These controls are particularly relevant when weak signal counts make accidental detections a larger fraction of the recorded events.

4.2 Residual coincidences

The measured heralded correlation is small but nonzero. Multipair emission, background detections, accidental coincidences, and timing effects may contribute. The present results establish suppressed multiphoton events but do not determine the contribution of each mechanism. A pump-power sweep and measurements at several coincidence-window widths would help distinguish them.

The fluorescent control is useful because it retains the same three-detector analysis while changing the source. Its correlation near unity shows that the suppression observed with SPDC cannot be attributed simply to adding a trigger detector or changing the analysis formula. The relevant distinction is the pair correlation that supplies useful heralding information [1].

4.3 Repeatability and uncertainty

Longer acquisitions generally reduce counting noise, but the unusually small reported 20 s standard deviation should be checked against the ten independent repeat records. A complete uncertainty budget should propagate singles and coincidence-count uncertainties through Equation (5), then assess repeatability and systematic effects separately. A standard deviation across repeated estimates is not itself a complete uncertainty budget.

The 1 s and 20 s means support the same qualitative conclusion: the heralded field strongly suppresses multiphoton events. Claims about absolute single-photon probability, heralding efficiency, or complete state purity would require additional measurements and cannot be inferred from the correlation value alone.

5 Conclusion

HBT and GRA measurements distinguished attenuated laser light, correlated SPDC photon pairs, and a fluorescent reference. The laser and unheralded SPDC arm gave measured correlations near unity, while the pair-source correlation was approximately 139. Conditioning on the partner-photon detection reduced the correlation to approximately 0.016, supporting heralded single-photon operation. The next steps are to verify the repeat statistics, quantify background and accidental coincidences, and improve collection alignment.

References

[1] Thorlabs. EDU-QOP1(/M) Quantum Optics Kit User Guide. MTN036012-D02, Rev. A, 16 June 2023. Sections 3.4–3.5, 3.9, and 9.1–9.5; experimental procedures on printed pp. 106–110. Figures 1–5 correspond to guide Figures 111–115.

[2] M. J. Collins et al. “Integrated spatial multiplexing of heralded single-photon sources.” Nature Communications 4, 2582 (2013). https://doi.org/10.1038/ncomms3582

Appendix Measurement records

Representative acquisition screens are retained below. Displayed single-run values may differ from the ten-measurement means in Table 1.

Figure 6. Representative 20 s HBT acquisition of the attenuated laser.

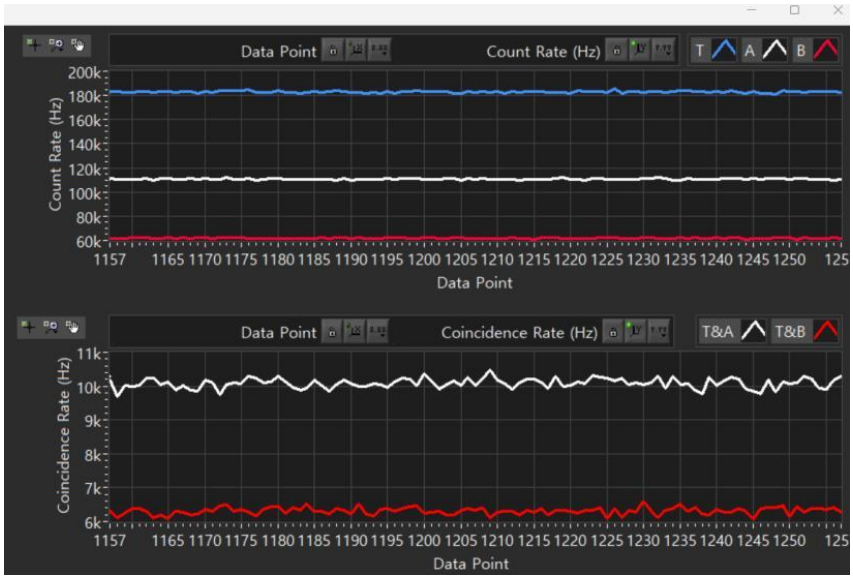

Figure 7. GRA singles: T (blue), A (white), B (red). Coincidences: T–A (white), T–B (red). The laboratory note lists a laser power of 35 mW.

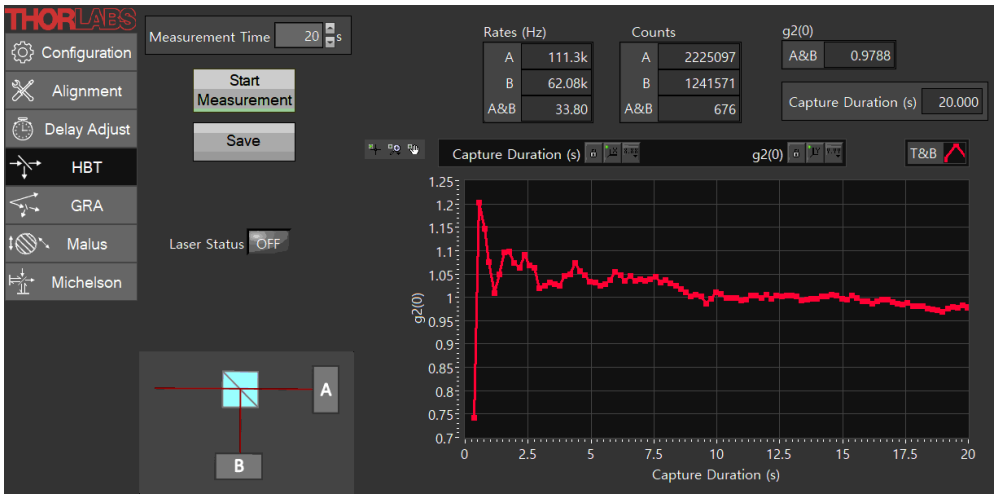

Figure 8. Representative 20 s HBT acquisition of one unheralded SPDC arm.

Appendix Heralded and classical reference records

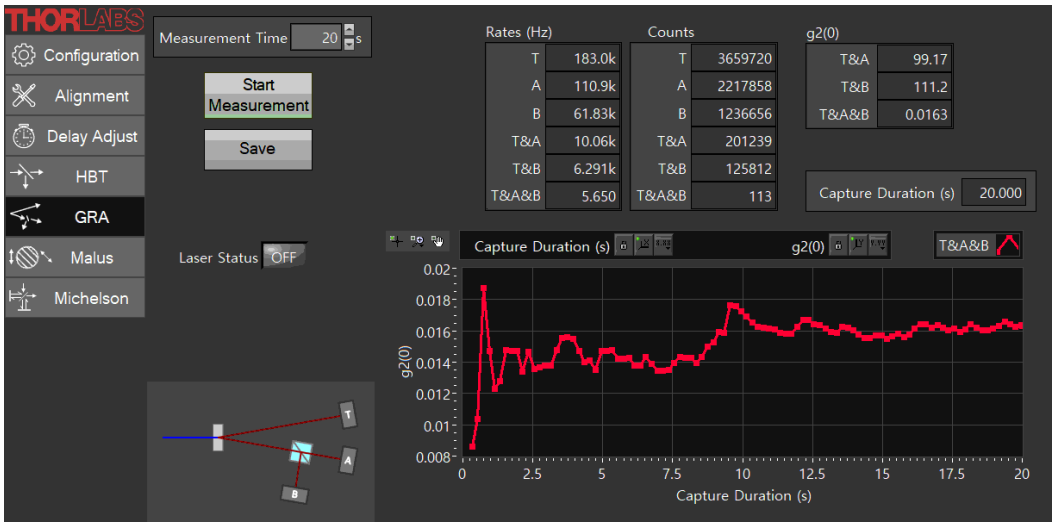

Figure 9. Representative 20 s GRA acquisition for the SPDC source.

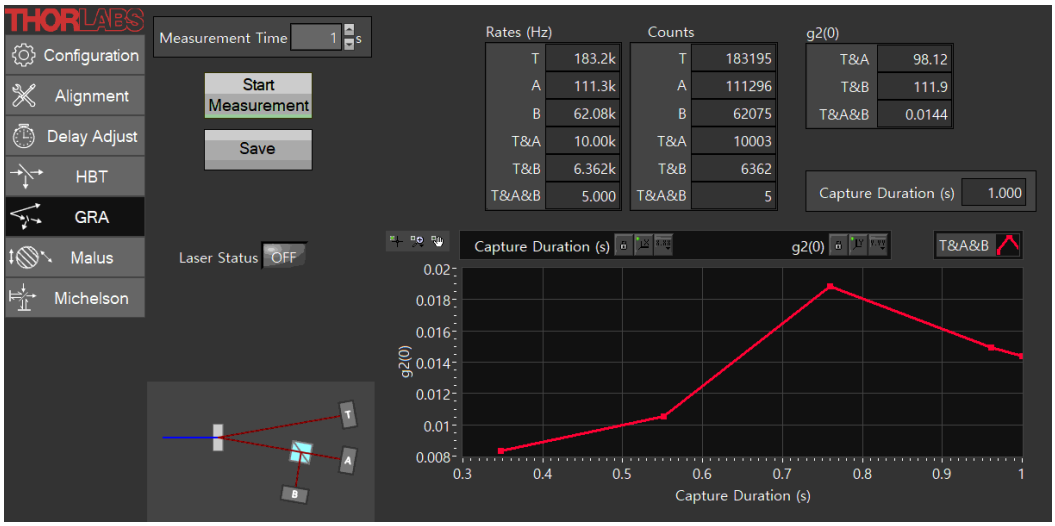

Figure 10. Representative 1 s GRA acquisition for the SPDC source.

Figure 11. Representative 20 s GRA acquisition with the fluorescent reference.