Photon Distributions Lab Report

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1 Introduction

Photon statistics lie at the core of many modern quantum technologies. The inherent randomness in the process of photon detection makes it a key resource for a wide range of applications, from quantum key distribution (QKD) to quantum random number generation (QRNG).
This randomness originates from the very principles of quantum mechanics, which describe nature in fundamentally probabilistic terms. As a result, in many electromagnetic fields (essentially in all experimental realizations) the number of detected quanta cannot be predicted deterministically but instead follows a specific probability distribution.

1.1 Coherent Fields

Coherent fields represent one of the most common and well-understood forms of electromagnetic radiation. Nearly all laser sources generate such fields, which are characterized by a Poissonian photon-number distribution. These fields exhibit remarkable stability in their average photon number, making them a cornerstone for both theoretical models and experimental implementations in quantum optics. In particular the probability of obtaining a particular photon count n is:

$$p(n) = \frac{\bar{n}^n \exp(-\bar{n})}{n!} \tag{1}$$

Their variance is $\sigma_n^2 = \bar{n}$.

1.2 Thermal Fields

Thermal fields represent a more chaotic field, and they are emitted according to the thermal equilibrium of the source. The probability distribution is in this case:

$$p(n) = \frac{1}{\bar{n}+1}\big(\frac{\bar{n}}{\bar{n}+1}\big)^n \tag{2}$$

where

$$\bar{n} = \frac{1}{\exp\big(\frac{hv}{kT}\big) - 1} \tag{3}$$

is the Bose-Einstein probability distribution. The variance in photon number for this type of source is now:

$$\sigma_n^2 = \bar{n} + \bar{n}^2 \tag{4}$$

The variance is a key factor in determining the type and quality of a photon source or the detection apparatus.

1.3 Arecchi Wheel

The Arecchi wheel is a simple yet elegant experiment that allows one to continuously tune between light fields that are approximately coherent and those that display thermal statistics. The idea is based on scattering a coherent laser beam off a rotating piece of sandpaper mounted on a motorized wheel. As the wheel spins, the random microstructure of the sandpaper introduces time-dependent phase and amplitude fluctuations in the reflected light, effectively scrambling its coherence.

In our setup, we explored two implementations of this concept. The first operated at 633 nm, where we detected the scattered photons using single-photon avalanche diodes (SPADs). The second used 1550 nm light, detected with superconducting nanowire single-photon detectors (SNSPDs) for higher sensitivity at telecom wavelengths. After reflection from the rotating sandpaper, the light was collected with a pinhole (for mode selection), a lens and collimator, ensuring stable spatial mode coupling into the detection system. This simple yet powerful configuration made it possible to observe the gradual transition from coherent to thermal photon statistics in a controlled and intuitive way.

2 Photon Distributions

We measured the photon distributions using a QuTau timetagger, which analyzes the electric impulses coming from the SPDs and assigns them precise timestamps in machine units, corresponding in our case to 81 ps. By grouping the events into bins of fixed temporal length, we can build a histogram of how many bins contain a given number of detected events. This histogram directly represents the photon number distribution.

We performed four measurements in total: two for each rotating wheel configuration (static/spinning), one for each wavelength/detector pair:

2.1 Static Wheel

For the static wheel configuration, we expect a Poissonian distribution. The reason is that the pinhole selects only a very small portion of the scattered light, effectively isolating a single reflection point on the sandpaper surface. The light reflected from this point retains the coherence of the incident laser, and thus should exhibit the photon statistics of a coherent state. The resulting distribution for the 633 nm laser detected with SPADs is shown in Fig. 1.
In order to verify this behavior, we fitted the experimental histogram with a Poissonian model, allowing us to directly compare the empirical photon statistics with the theoretical distribution expected for a coherent source.

The computed mean photon number and variance per bin are:

$$\bar{n} \approx 254.42 \qquad \sigma_n^2 \approx 299.62 \,(\text{expected } 254.42) \tag{5}$$

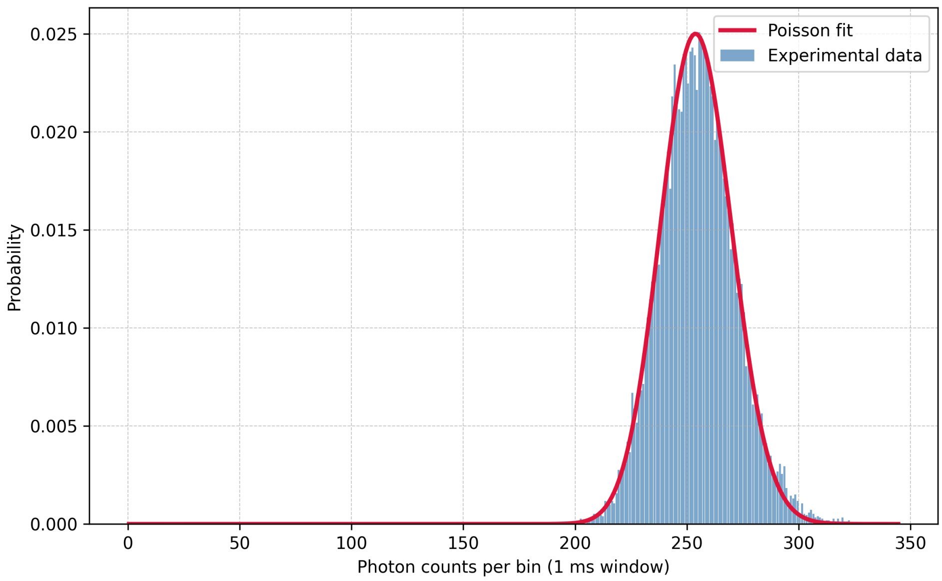

Figure 1: Photon distribution for static wheel (633 nm laser with SPAD)

While the values are not perfectly identical, they are close enough to be considered consistent with the expected Poissonian behavior.

In the 1550 nm measurement with SNSPDs, despite the lower optical power, the higher detection efficiency provides a clearer statistical match, as shown in Fig. 2.

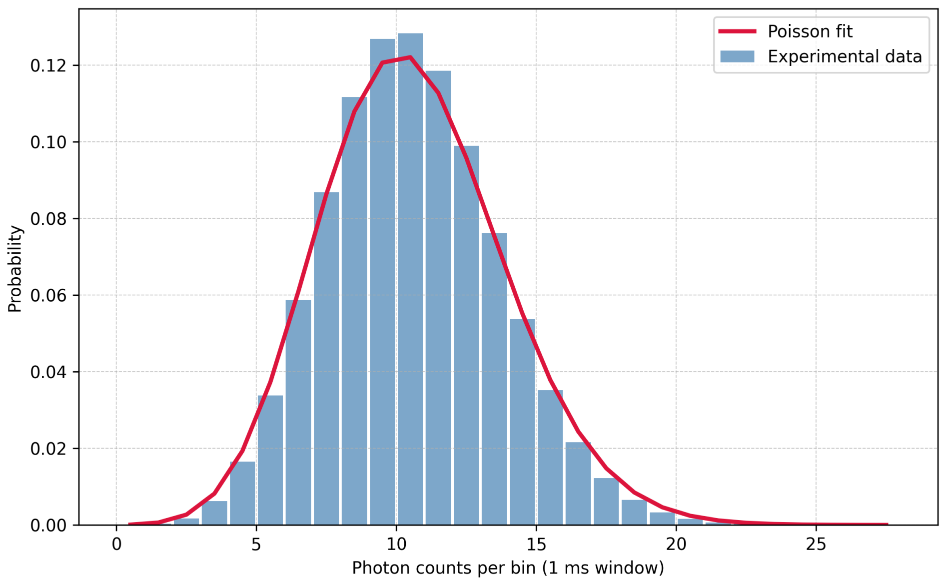

Figure 2: Photon distribution for static wheel (1550 nm laser with SNSPD)

$$\bar{n} \approx 10.08 \qquad \sigma_n^2 \approx 9.50 \,(\text{expected } 10.08) \tag{6}$$

Here, the mean and variance almost perfectly coincide, confirming the Poissonian nature of the light field. In both static cases, the visual distribution and the statistical fingerprint (variance $\approx$ mean) strongly support the interpretation of a coherent source.

2.2 Spinning Wheel

When the wheel is spinning, the scattered light originates from many random points on the rough surface, which rapidly decorrelates the phase and amplitude of the field. The initially coherent laser light is thus transformed into a chaotic (thermal) source. In this case, we expect a geometric photon number distribution.

To confirm this, we fitted the histogram with a thermal distribution model and compared it with the measured data to check how closely it followed the theoretical expectation. Figure 3 shows the distribution obtained for the 633 nm laser detected with SPADs. The histogram now has a completely different shape: the most frequent outcome corresponds to an empty bin, a hallmark of the thermal (geometric) distribution. To better highlight the statistics, a smaller bin width was chosen. For this case:

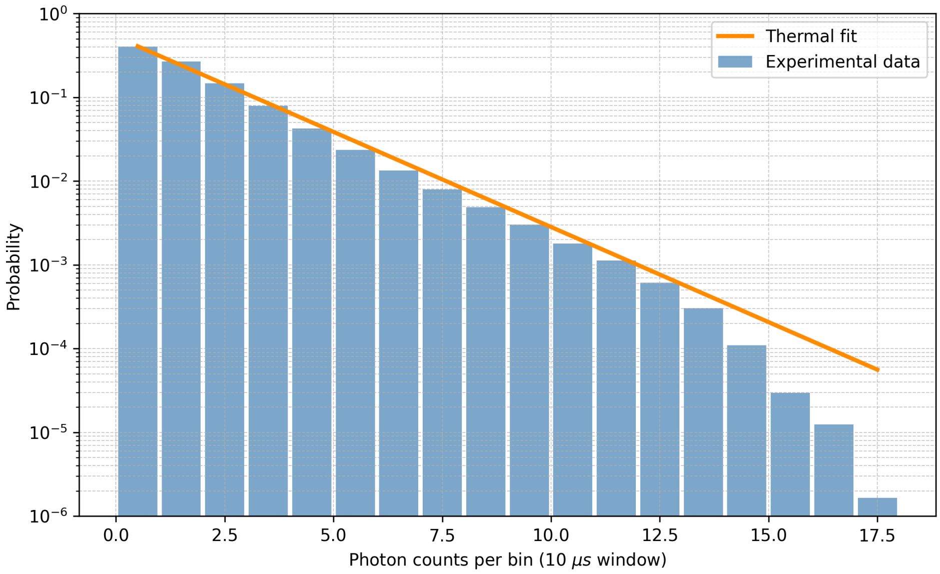

Figure 3: Photon distribution for spinning wheel (633 nm laser with SPAD)

$$\bar{n} \approx 1.33 \qquad \sigma_n^2 \approx 2.98\,(\text{expected } 3.09) \tag{7}$$

The agreement with the theoretical prediction is again very good. Minor deviations can be attributed to experimental imperfections and detector efficiency limits. With a higher detection efficiency, we would expect an even closer match to theory. The corresponding 1550 nm measurement with SNSPDs is shown in Fig. 4.

$$\bar{n} \approx 10.14 \qquad \sigma_n^2 \approx 90.77\,(\text{expected } 112.96) \tag{8}$$

In this case, the distribution shows a truncation of the high-count region, which explains the deviation from the theoretical curve. It is worth noting that the apparent shape of the distribution depends on the chosen bin size: larger bins average over more fluctuations, pushing the statistics closer to Poissonian behavior, while smaller bins reveal the super-Poissonian nature of thermal light. Detector jitter and timing precision also contribute to this effect, in agreement with the central limit theorem, which predicts that repeated random sampling tends toward a Gaussian distribution in the large-sample limit.

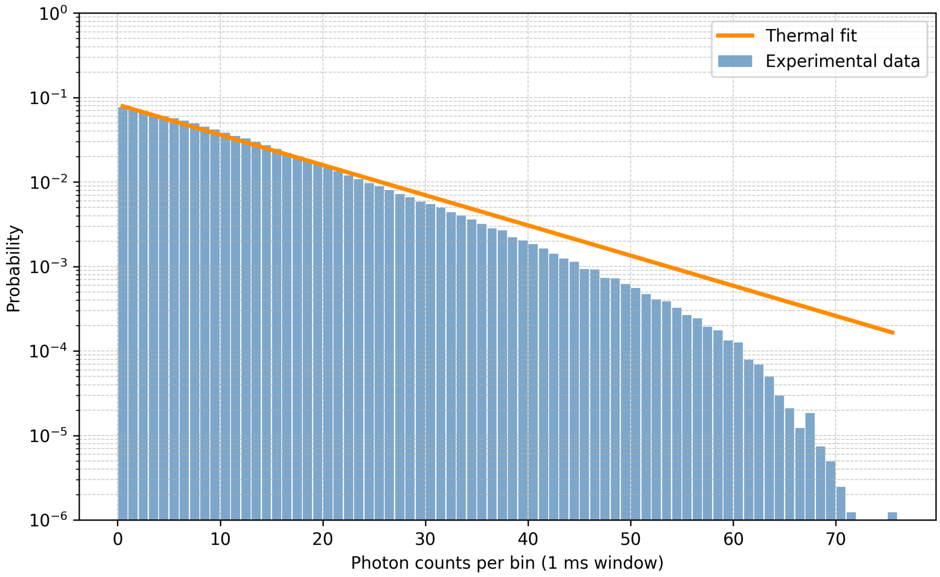

Figure 4: Photon distribution for spinning wheel (1550 nm laser with SNSPD)

3 QRNG

One practical motivation for studying photon statistics is the generation of true random numbers. Quantum processes are inherently random, and thus provide a way to go beyond the pseudo-randomness of classical computational methods.

Our method generates random points in a discrete 3D space by comparing pairs of timestamp differences between subsequent detection events, $\Delta_i = t_{i+1} - t_i$:

- if $\Delta_i > \Delta_{i+1}$ we assign 1
- otherwise we assign 0

The resulting bit stream is grouped into bytes (8 bits), representing integers between 1 and 255. These are then grouped in triplets and interpreted as 3D Cartesian coordinates in a $255 \times 255 \times 255$ space. Plotting the resulting cloud of points gives a visual representation of the randomness quality.

We performed this procedure for both the static and spinning wheel setups with the 633 nm laser and SPAD detection, obtaining the distributions shown in Fig. 5 and Fig. 6.

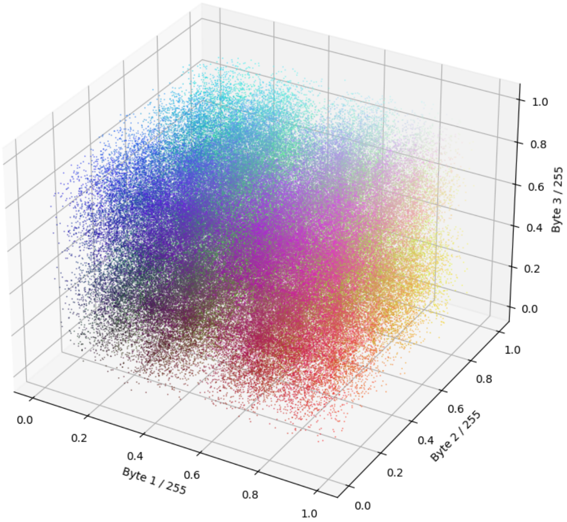

Figure 5: QRNG fog in the static wheel setup

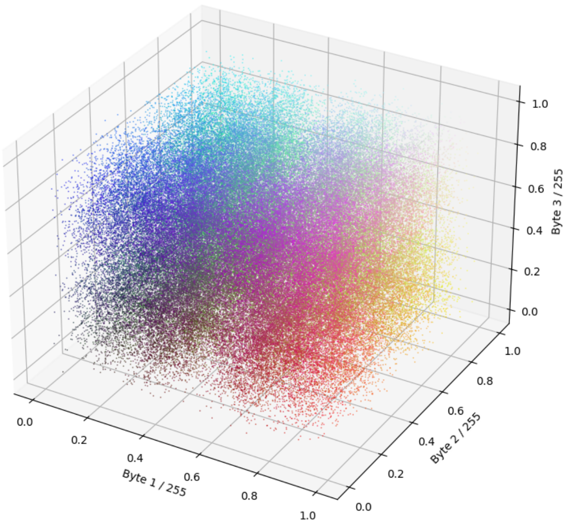

Figure 6: QRNG fog in the spinning wheel setup

4 Conclusions

The experimental results, after careful postselection and analysis, show a strong correspondence with the theoretical photon statistics expected for the respective light fields. In the static wheel configuration, the observed distributions closely followed a Poissonian model, confirming the coherent nature of the detected light. In contrast, the spinning wheel setup produced distributions well described by a thermal (geometric) model, as expected from a randomized, incoherent source.

While small deviations from theory were present, mainly due to detector imperfections, electronic noise, and the practical limits of our binning resolution, the overall agreement demonstrates that the experimental setup and analysis are sound. The fits between empirical data and theoretical models provide clear evidence that the photon statistics behave as predicted for coherent and chaotic light.

Regarding the quantum random number generation (QRNG) experiment, the generated point cloud appeared fairly uniform, confirming that even a simple extraction protocol based on photon arrival times can yield a reasonable degree of randomness. Nonetheless, this remains a very basic approach compared to the state-of-the-art techniques used in current research, which employ more complex entropy extraction and statistical validation methods to ensure provably secure randomness.

Overall, the results validate both the physical models underlying the photon statistics and the experimental procedures used to observe them. The work provides a clear, hands-on demonstration of the statistical nature of light fields and highlights how such phenomena can be directly linked to practical applications such as quantum random number generation.