Photon Indivisibility

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1 Introduction

Quantum optics treats light as a sea of quanta (photons) which behave as localized excitations of the electromagnetic field. But one may ask: what happens when light is split at a 50/50 beam splitter and we dim it down to the single-photon level? This question lies at the heart of O. R. Frisch's famous paper "Take a Photon" [1], which analyzes the conflicting interpretations of such an experiment and how they clash with experimental reality. Frisch begins by noting that passing a beam through a beam splitter does not alter its wavelength, and therefore not the energy of a single photon. It seems natural, then, to conclude that a photon must "choose" one path or the other. Yet experiments reveal that the situation is subtler: single photons can interfere with themselves, indicating the persistence of wave-like coherence even when energy detection remains quantized. Demonstrating that a photon remains indivisible at the beam splitter is therefore both conceptually and experimentally challenging, and this is precisely where our investigation begins.

2 Setup

In order to be able to prove the indivisibility of the photon, we start from a "modernized" version of the setup used in the first experiment of this kind[2] by using an entangled photons source.

2.1 Entanglement Source

In order to generate entangled photons we start with a laser, which through Type II degenerate SPDC, obtained thanks to orthogonally oriented BBO crystals, allows us to create a pair of entangled photons in the Bell state

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}\big(|HV\rangle + |VH\rangle\big) \tag{1}$$

In our free-space implementation, the photons are collected through pinholes at the intersection of the generation cones.

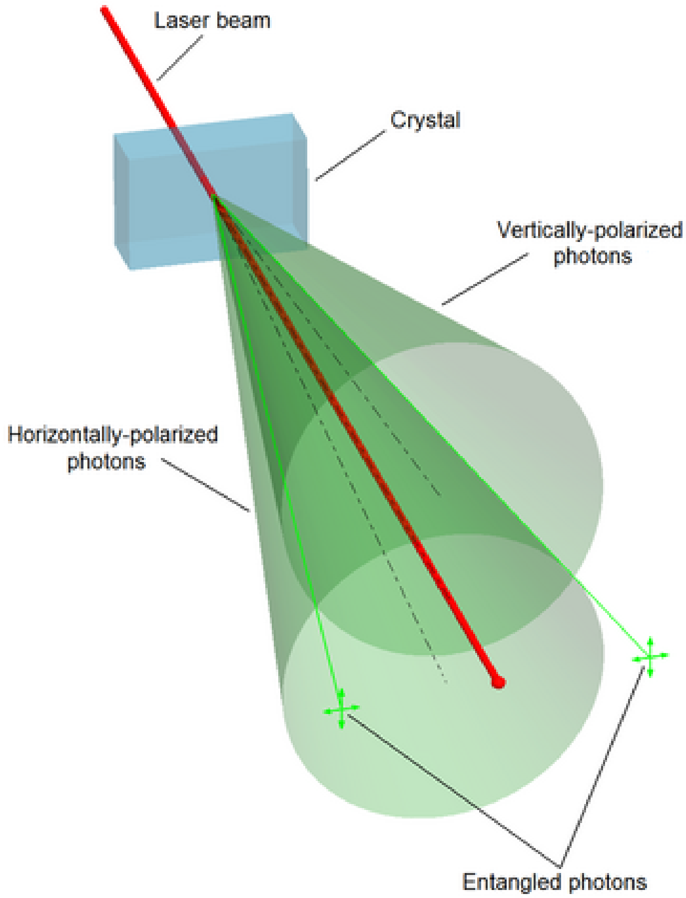

Figure 1: Output of SPDC

2.2 Working Principle

At this stage, one of the photons is directed to a single-photon avalanche diode (SPAD) for detection and is referred to as the heralding photon. The other photon is sent to a 50:50 beam splitter, whose two output ports are each monitored by a SPAD to determine the photon's path. By exploiting indistinguishable photon pairs (photons perfectly overlapping in their temporal mode) we effectively suppress detection noise and mitigate the impact of unequal detector efficiencies when analyzing the beam splitter outcomes. This heralded configuration allows us to post-select only events that correspond to genuine single-photon detections, thereby improving the signal-to-noise ratio (SNR) of the measurement by several orders of magnitude.

3 Measurements

Through seven independent measurements, we obtained the following number of counts for the different detection channels:

$$N_H(\text{Heralding}) = 8{,}023{,}348$$
$$N_t(\text{Transmitted}) = 2{,}504{,}793$$
$$N_r(\text{Reflected}) = 2{,}196{,}306$$
$$N_{\text{TOT}} = 12{,}724{,}447$$

3.1 Field Statistics

We first examine the photon statistics for each of the detected fields.

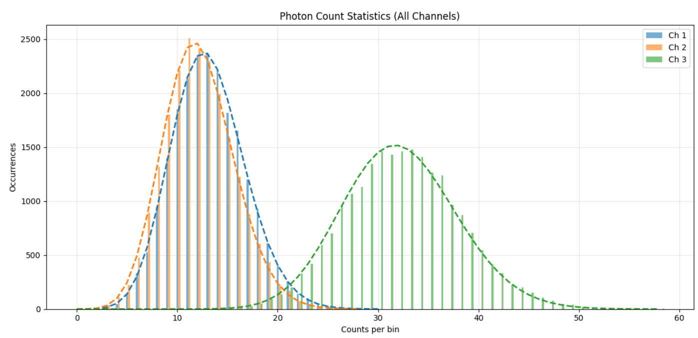

Figure 2: Photon number statistics for each detection channel. The distributions exhibit the expected Poissonian behavior typical of coherent states.

By clustering photon detection events into discrete time bins and counting the number of bins containing a given number of detection events, we reconstruct the photon number distributions. Starting from a standard laser source, we expect a Poissonian distribution characteristic of a coherent state for each channel, which is clearly observed in Fig. 3.

Although nonlinear processes such as spontaneous parametric down-conversion (SPDC) can induce non-classical field modifications (e.g., squeezing), the measured statistics

$$\begin{aligned}
&\text{Channel 1:} \quad \bar{n}_1 = 13.127, \quad \sigma_1^2 = 13.290,\\
&\text{Channel 2:} \quad \bar{n}_2 = 12.197, \quad \sigma_2^2 = 12.254,\\
&\text{Channel 3:} \quad \bar{n}_3 = 32.180, \quad \sigma_3^2 = 33.266.
\end{aligned}$$

align very closely with Poissonian statistics, confirming that each field behaves coherently. As expected, the mean count in Channel 3 is approximately double that of the split outputs, since it does not undergo beam splitting. The slight imbalance (where Channels 1 and 2 record fewer than half the counts) can be comfortably attributed to additional optical losses in the respective detection paths.

3.2 Time Correlation

Through the use of time-bins for coincidences between each of the transmitted and reflected beam splitter paths and the heralding photon of 0.1 ns, we can plot the time-domain correlation function between the photon counts in the two cases:

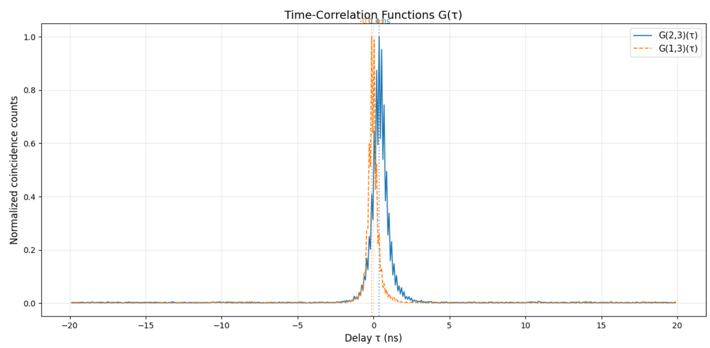

Figure 3: Normalized time-correlation functions between the heralding photon and each of the two output paths of the beam splitter.

The correlation functions are normalized to their maximum value, allowing for a direct comparison between the two channels. We observe two sharp coincidence peaks centered respectively at delays of -0.129 ns (transmitted) and 0.369 ns (reflected), corresponding to optical path length differences of approximately -3.87 cm and 11.07 cm. These time offsets arise from small asymmetries in the optical paths traversed by the photons before reaching the detectors, consistent with fiber length differences or beam splitter alignment tolerances. The so-called *Bell widths* (FWHM) of the two peaks are found to be 0.492 ns and 0.656 ns, respectively. These widths quantify the temporal extent over which the heralded detection events are correlated. The well-defined and narrow peaks indicate precise timing correlations between the heralding and heralded photons, confirming that the photon-pair generation and detection processes are temporally well resolved. Any broadening of these peaks would signal increased timing jitter or imperfect synchronization in the detection system.

Overall, the distinct and normalized peaks demonstrate that the detected coincidences originate from true photon-pair events and that the timing correlation between the herald and the signal photons is well preserved across both detection channels.

3.3 Coincidence Counts

Through a coincidence window of 1 ns (deemed appropriate in light of the Bell width measurements discussed in Subsection 3.2) the heralded counts for each of the outputs of the beam splitter show a pronounced imbalance. This can be attributed to experimental imperfections, though the specific source is difficult to analyze in a single-shot experiment. It is worth recalling that the timetagger channels 1, 2, and 3 correspond to the transmitted, reflected, and heralding photons, respectively:

$$\begin{aligned} N_{13} &= 131{,}976 \\ N_{23} &= 34{,}050 \\ N_{3} &= 8{,}023{,}348 \end{aligned}$$

The number of triple coincidences, however, falls within expectations with remarkable precision:

$$N_{123} = 4 \tag{2}$$

3.4 Quantitative Measurement of Quantum Behavior

As derived by G. Grangier *et al.* [2], the inequality

$$p_c \geq p_r p_t, \tag{3}$$

which relates the probability of observing a coincidence (p_c) to the singles probabilities in the reflected (p_r) and transmitted (p_t) arms, directly follows from the Cauchy–Schwarz inequality applied to the intensity correlations of a classical electromagnetic field. This represents a fundamental constraint imposed by classical light statistics.

The same relationship can be expressed in terms of the α parameter:

$$\alpha = \frac{p_c}{p_r p_t} = \frac{N_{123} N_3}{N_{23} N_{13}}, \tag{4}$$

for which any classical field must satisfy

$$\alpha \geq 1. \tag{5}$$

A violation of this bound thus reveals anticorrelation between detections at the two beam splitter outputs, providing direct evidence of photon indivisibility and the nonclassical nature of the light field.

Using the data presented above, we obtain:

$$\alpha = 0.0071 \pm 0.0036, \tag{6}$$

which constitutes a violation exceeding 256 standard deviations—an unambiguous confirmation of nonclassical behavior.

Assuming Poissonian statistics for all count rates (as discussed in Section 3) and applying standard error propagation, the uncertainty is given by:

$$\sigma_\alpha = \alpha \sqrt{\frac{1}{N_{123}} + \frac{1}{N_3} + \frac{1}{N_{13}} + \frac{1}{N_{23}}}. \tag{7}$$

It is interesting to compare the results for the α parameter in two distinct situations: with and without a flashlight pointed at the setup. This comparison provides a rough comparison between ranges of signal-to-noise-ratio (SNR) at the detectors, and it is carried out by analyzing the data from the files `TimeTags.txt` (without) and `TimeTags_6.txt` (with).

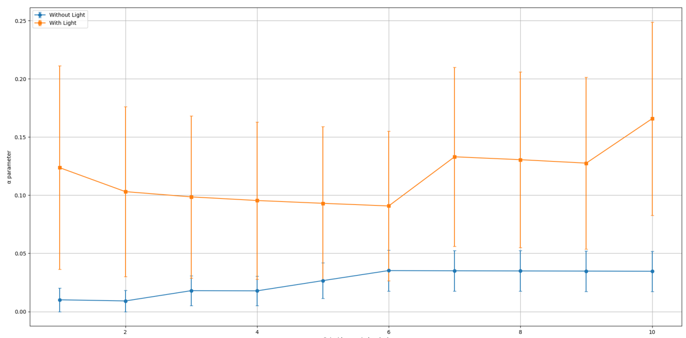

Figure 4: α parameter as a function of the coincidence window width.

The results shown in Fig. 4 highlight that, in the case of a low SNR, a smaller α value can be obtained by restricting the coincidence window, effectively suppressing noise contributions. As the window size increases, α rises accordingly. Conversely, when the flashlight is introduced, the α parameter exhibits a much larger standard deviation and shows little sensitivity to changes in the coincidence window width, suggesting that the added noise behaves as an uncorrelated background relative to the coincidence statistics across the different channels.

4 Conclusions

Despite the presence of experimental imperfections, such as the pronounced imbalance observed between the coincidence counts of the beam splitter outputs and the heralding photons, we have demonstrated, with extremely high confidence, the indivisibility of the photon by observing a clear anticorrelation in the heralded detections at the two outputs of the beam splitter.

By reproducing and modernizing a landmark experiment that marked a turning point in the development of quantum optics and the foundations of quantum physics, we achieved a confidence level in the violation of classical predictions approximately twenty times greater than that reported in the original work, even without extensive optimization or repeated measurements. This constitutes a remarkable confirmation of the quantum nature of light and a testament to the precision attainable with contemporary single-photon detection techniques.

References

[1] O. R. Frisch, ""take a photon . . ."", Contemporary Physics **7**, 45–53 (1965).

[2] P. Grangier, G. Roger, and A. Aspect, "Experimental evidence for a photon anticorrelation effect on a beam splitter: a new light on single-photon interferences", Europhysics Letters **1**, 173–179 (1986).