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Report 2 - Photon anti-correlation effect on a beam splitter

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The discreteness in the energy content of light is reported in experiments ranging from the black-body spectrum to the photo-electric effect: such phenomena underlie the unique sense in which a photon is regarded as an indivisible particle, experimentally tied to the fact that a beam splitter does not split a single photon of a two-photon pair. What seems today as an objective reality, once was not: from Einstein's 1905 idea, the conclusive experiment on the necessity of the photons demonstrating its indivisibility was carried out only in 1986 by *Grangier et al.*[1].

In this report we replicate the experiment described in [1] that

> "[...] shows a strong anticorrelation between the triggered detections on both sides of a beam splitter."

and is consequently

> "[...] in contradiction with any classical wave model of light, but in agreement with a quantum description involving single-photon states."

1 Experimental setup

The experimental setup consists in a laser source and a non-linear crystal that emits pairs of photons with different frequencies ν_1 and ν_2 via spontaneous parametric down conversion (SPDC). This phenomenon, also known as parametric fluorescence or parametric scattering, is a nonlinear instant optical process that converts one photon of higher energy (namely, a **pump photon**), into a pair of photons (namely, a **signal photon**, and an **idler photon**) of lower energy, in accordance with the law of conservation of energy and law of conservation of momentum. The detection of ν_1 (heralded or idler photon) acts as a trigger for a gate generator, enabling two single photon detectors (SPD) in view of ν_2. These two are placed on both sides of a 50/50 beam splitter (BS), and feed singles' and coincidences' counters.

In Fig. 1 a schematic representation of the setup is shown: the detection of the idler photon produces a time window τ_c, during which the photomultipliers $\text{SPD}_{1,2}$ and $\text{SPD}_{1,3}$ are active. The second subscript numbers identify the channel for reflected and transmitted photons respectively (see Section 3).

2 Theoretical background

We denote with N_1 the number of idler events detected at SPD_1; N_{123} are triple coincidences between SPD_{123} while $N_{12,13}$ are the coincidences between $\text{SPD}_{1,2}$ $\text{SPD}_{1,3}$ inside the time window τ_c, respectively. The probabilities for singles' counts during a time window τ_c are given by

$$p_r = \frac{N_{12}}{N_1} \qquad\qquad p_t = \frac{N_{13}}{N_1} \tag{1}$$

while for a coincidence it holds $p_c = N_{123}/N_1$. Now, during τ_c, the probability for the detection of a photon ν_2 coming from the same event that generated ν_1 is much bigger than the probability of detecting a photon ν_2 emitted by any other event - for instance, a photon not belonging to the

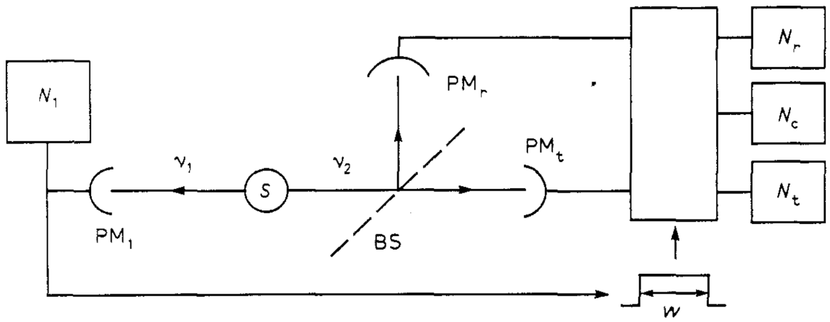

Figure 1: Experimental setup, as shown in the original paper [1].

pair that comprises ν_1 or noise. We are then in a situation close to an ideal single-photon state emission, and we can expect the characteristic behaviour of such a state, i.e. an anticorrelation between detections occurring on both sides of the beam splitter.
Considerations using the Cauchy-Schwartz inequality and arguments involving the intensity $I(t)$ impinging on the beam splitter yield for the counting rates to

$$p_c \geq p_t \cdot p_r \tag{2}$$

which is equivalent to

$$\alpha \geq 1 \text{ with } \alpha = \frac{p_c}{p_r \cdot p_r} = \frac{N_{123}N_1}{N_{12}N_{13}}, \tag{3}$$

which can be interpreted as the classical coincidence probability p_c being always greater than the accidental coincidence probability (equal to the product $p_t p_t$). The violation of Eq. (3) thus gives an **anticorrelation criterion** for characterising a non-classical behaviour.
α is used in other contexts as figure of merit to quantify the quality of the single photon source and is also referred to as the (idler-triggered) second-order autocorrelation function $g^{(2)}_{s,s}(0)$ [2], where $g^{(2)}_{s,s}(\tau)$ describes the situation where an idler and a signal photon are detected at time $t = 0$ with a second signal photon at $t = \tau$. $g^{(2)}_{s,s}(0)$ can be written as in Eq. (3) ($g^{(2)}_{s,s}(0) \equiv \alpha$) for small windows $[-\tau_c/2, \tau_c/2]$ around $\tau = 0$.

3 Dataset

The data were collected for a total of $T = 1800\,\mathrm{s}$ in 5-minute intervals and contain both the time tags of the photon incidences (in seconds) and the corresponding channels, identified by a numerical tag:

- **2** for the **reflected** channel;
- **3** for the **transmitted** channel;
- **4** for the **herald** channel.

For the conversion in machine units (m.u.) it holds $1\,\mathrm{m.u.} \equiv 81\,\mathrm{ps}$.

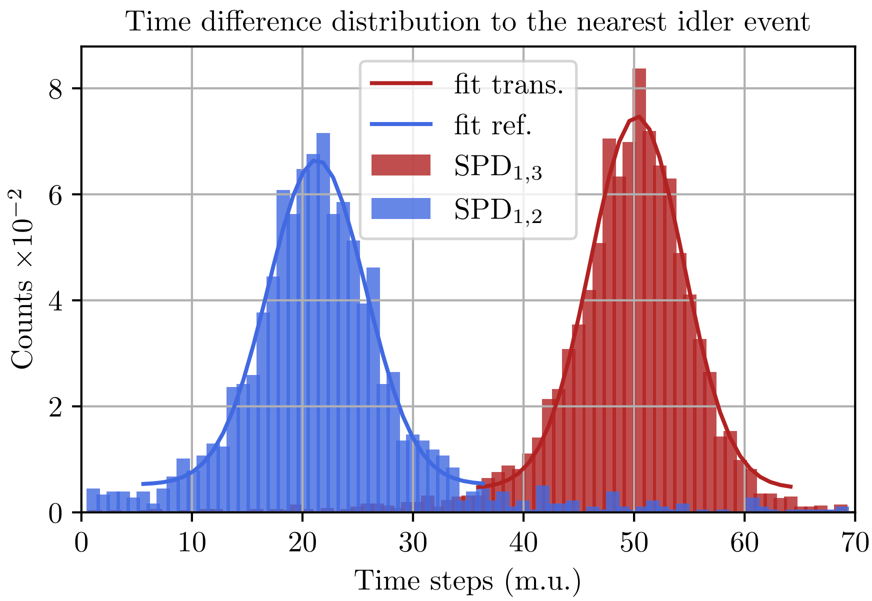

Figure 2: Histogram of the time difference distribution between each detector and the nearest gate click.

4 Analysis and discussion

First, the time delay between transmitted/reflected and idler counters were computed: in order to consider just the closest detections, only the values greater than a certain threshold were kept. This threshold was chosen to be arbitrarily $\approx 6\,\text{ns}$. It has been observed that this choice does not affect the following analysis and is thus treated only as an indicative value. The resulting (normalised) histograms (Fig. 2) follow a gaussian distribution, as expected for correlated arrival times: the distribution is no more exponential, which would be typical of uncorrelated events. The two histograms are then fit to find the best parameters for average and width of the reflected and transmitted distributions: the results are reported in Table 1.

Practically, counting the coincidences N_{123} and $N_{12,13}$ is realised by opening a coincidence window

SPD	$\mu_{t/r} \pm \sigma_\mu$	$\sigma_{t/r} \pm \sigma_\sigma$
$1,2$	50.3 ± 0.1	4.2 ± 0.2
$1,3$	21.3 ± 0.1	4.4 ± 0.2

Table 1: Parameters found by interpolation of the distributions in Fig. 2.

of width $\tau_c = 2 \cdot M \cdot \sigma_{t/r}$ symmetrically around the detection of an idler photon: M is a multiplicative constant that is progressively enlarged in order to include more and more events. Then, to determine $N_{12,13}$ we measure events on either signal detector (double coincidence), while events on both signal detectors (three-fold coincidences) are added up to N_{123}; N_1 is the number of correlated events (equal to the number of heralded photons).

It has been observed that $N_c \neq 0$ only for a time window $\tau_c^r = 38.6\,\text{ns}$, $\tau_c^t = 36.95\,\text{ns}$ for reflected and transmitted photons respectively. Fig. 3 shows the dependence of $g^{(2)}_{s,s}(0)$ on the idler (heralding)

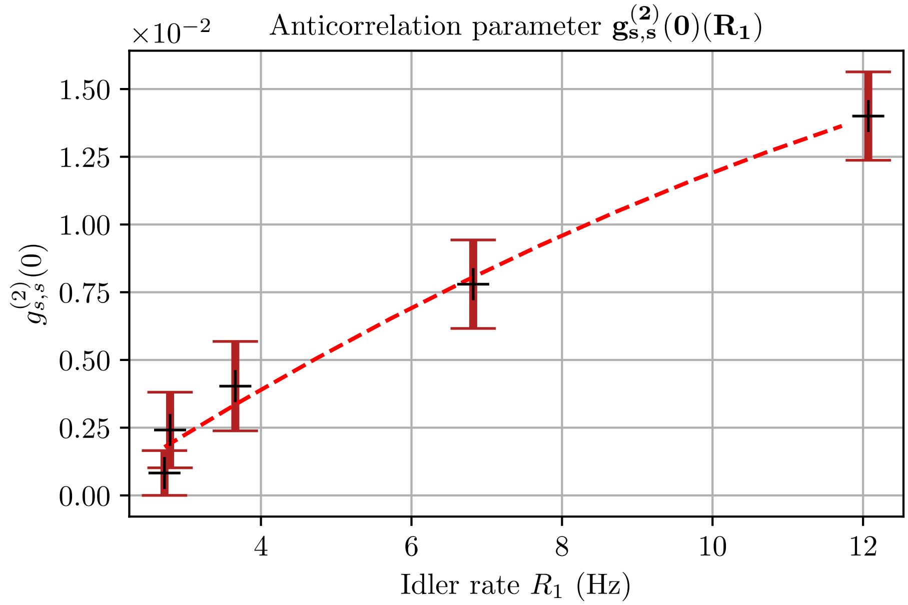

Figure 3: Idler-triggered second-order autocorrelation function $g^{(2)}_{s,s}(0)$ dependent on the heralding rate R_1, red line as a guide for the eye.

rate $R_1 = N_1/T$, where T is the overall measurement time. Each data point is not corrected for dark counts which would further reduce $g^{(2)}_{s,s}(0)$. The minimum measured value achieved is of $g^{(2)}_{s,s}(0) = (8.3 \pm 8) \cdot 10^{-4}$ (lower than the classical limit by ~ 1200 standard deviations) for a idler rate of 2 Hz, giving clear proof of the quantum character of the single photon source.

5 Conclusion and outlook

The anticorrelation parameter $g^{(2)}_{s,s}(0) < 10^{-3}$ confirms the single photon nature of our source. The next step would be to increase the acquisition time in order to produce a more satisfactory statistics. Furthermore, a correct treatment of the effects due to the noise of the experimental setup (namely dark counts and afterpulse) is due, a discussion that would further improve the estimate of $g^{(2)}_{s,s}(0)$.

[1] P. Grangier, G. Roger, and A. Aspect, Europhysics Letters **1**, 173 (1986).
[2] M. Rambach, A. Nikolova, T. J. Weinhold, and A. G. White, APL Photonics **1**, 096101 (2016).