quED-HBT

Hanbury-Brown-Twiss Add-On

quED-HBT Manual V1.0

quED-HBT Manual V1.1 (July 28, 2022)

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1.1 Quickstart Manual

The HBT Add-On for the quED consists of an additional single photon detector module installed in the quCR and a fiber based beam splitter.

Installing the additional detector module

ATTENTION: Never plug in or pull out detector modules while the quCR is running. The electronics could be damaged.

If not already supplied that way, the additional detector module has yet to be inserted into the quCR. Follow these steps to do so:

- Make sure the quCR is turned off and the power cord is disconnected.
- Remove the cover at the rightmost end of the quCR, beside the already mounted detector.
- Gently push the new detector into the now accessible slot. Be especially careful during the last few millimeters, when the connector is plugged in.
- Fasten all 4 screws of the module.

If the additional count rate and the corresponding coincidences are not already shown in the countrate tab, they first have to be activated in the quCR (see also the quCR manual for more detailed information):

- Change in the expert mode of the quCR with the code on the qutools logo in the *quInfo* module.
- Select the desired channels in the display *quInfo: Rates Configuration*.
- Restart the quCR.

Connection of the beam splitter

Remove the fiber connected to the detector channel 1 and connect this free end to the input of the fiber beam splitter using an I-connector. Connect both ouptuts of the beam splitter to the detector channels 1 and 2 as in Fig. 1.1.

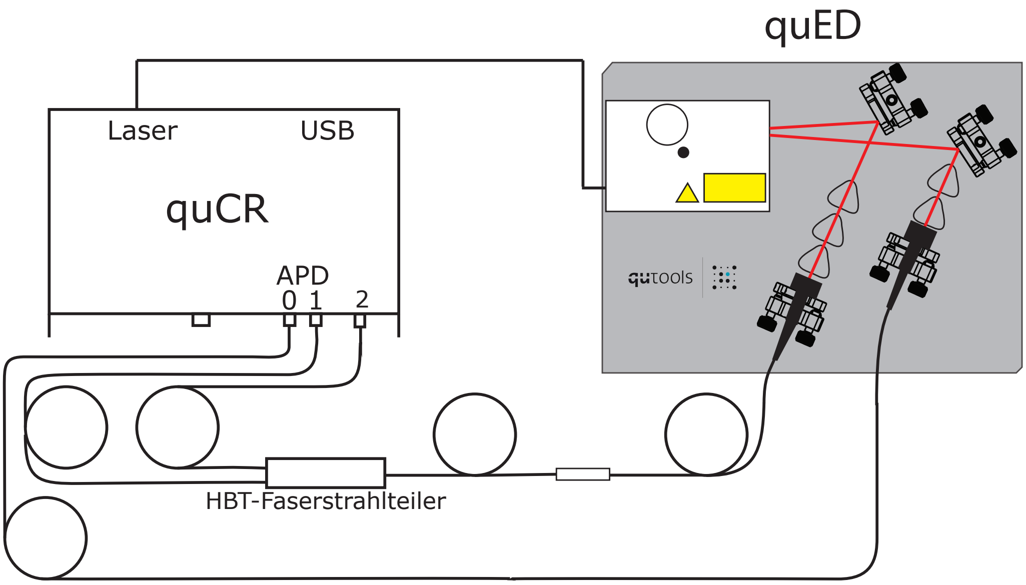

Figure 1.1: Schematic setup of the HBT Add On.

2 Experiments with the quED-HBT

2.1 Hanbury Brown-Twiss: The $g^{(2)}$ function

The Hanbury Brown-Twiss Experiment allows to investigate the particle nature of a source of photons. Is really ever only one photon (pair) detected at once, or are these wave packets that can be split in half?

2.1.1 Theory

Quantum Nature of Light

The quantum theory of light predicts that electromagnetic radiation only exists in quantized energy packets. The smallest possible energy packet is called "‘photon"’, it can not be split into smaller packets.
In contrast classical electromagnetic radiation described by Maxwell's equations allows any field energy. Even very small electric fields can be split into two. In this case, the measured intensity is proportional to the square of the electric field amplitude.

Experimental verification

"Photon counting detectors" - for example a photomultiplier or an avalanche photodiode - register single detection events [4]. If only one detector is used it is not clear if the detection of single events is a property of the detector or the light field. The Hanbury Brown-Twiss [1] setup - two detectors behind a beamsplitter as in Fig. 2.1 - can be used to prove the quantization of the electromagnetic field[1]. In the classical theory of the electromagnetic field, both detectors behind a beamsplitter will register a detection event at the same time (with some detection efficiency E). In contrast, the quantized field displays particle like behavior. If the energy in front of the beam splitter is the smallest possible energy packet (one photon) only one of the two detectors can register an event at the same time.

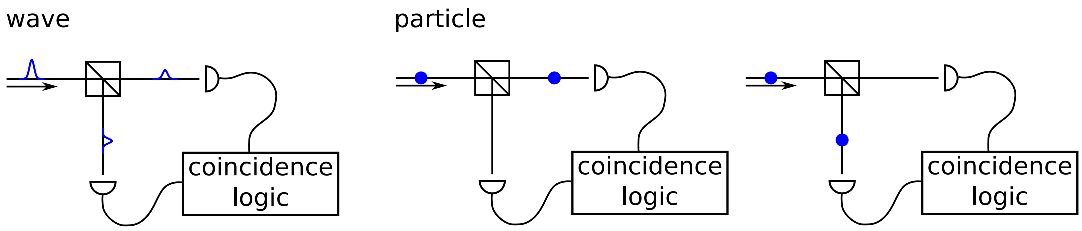

Figure 2.1: Difference between wave and particle at a beamsplitter.

Typically, one measures the second order correlation function $g^{(2)}(\tau)$ function of a beam of light using the above mentioned beamsplitter. Clasically, it is given by the correlations of the output intensities

$$g^{(2)}(\tau) = \frac{\langle I_1(t+\tau) I_2(t) \rangle}{\langle I_1(t+\tau)\rangle \langle I_2(t)\rangle} \ . \tag{2.1}$$

For our purposes, it is sufficient to look at the $\tau = 0$ case. Also, because our detectors measure only single events, we can replace the intensities by probabilities and write

$$g^{(2)}(0) = \frac{P_{12}}{P_1 P_2} \ , \tag{2.2}$$

where $P_{1,2}$ is the probability to detect a single event at detector 1 or 2, respectively, in a short time interval t_c and P_{12} is the probability of making detections in both detectors in the same interval. Therefore, t_c is also called *coincidence time interval* or *coincidence (time) window*. It can be shown that classical light allows only for values of $g^{(2)}(0) \geq 1$ whereas $g^{(2)}(0) < 1$ can be realized by quantized light.

In the actual experiment one measures count rates (counts per second)

$$R_{1/2} = \frac{P_{1/2}}{t_c} \tag{2.3}$$

and not probabilities, so we get

$$g^{(2)}(0) = \frac{R_{12}}{R_1 R_2 t_c} \ . \tag{2.4}$$

[1]Interestingly, Hanbury Brown and Twiss originally did not use a beam splitter and worked on a seemingly unrelated task: they determined the apparent angular size of the star Sirius using two photomultiplier tubes spaced 6 meters apart.

When only individual photons are measured, which means that no photons are generated directly following one another, then R_{12} and with it $g^{(2)}(0)$ is equal to zero. This effect is called *antibunching*. With purely random photon emissions, e.g. from a laser, $g^{(2)}(0) = 1$ should hold. With thermal sources, such as a light bulb, the value rises above one, this is called *bunching*.

Photon Pair Sources

The quantization of the electromagnetic field can also be demonstrated using photon pair sources. One photon is guided to the first detector. Two detectors behind a beamsplitter can register the second photon (Fig. 2.2). If the electromagnetic field is quantized all three detectors should seldom register an event at the same time. Clauser used an atomic cascade source and showed that his results could not be explained by classical field theories [2]. Hong and Mandel used photon pairs from a spontaneous parametric down-conversion source [3].

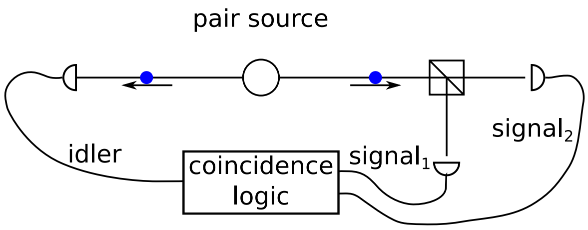

Figure 2.2: Photon anticorrelations of a pair source

The $g^{(2)}$ function for heralded photons

Frequently, experiments with a second source beam that is used as a trigger are performed, for example with down conversion sources. In this case, eq. (2.2) has to be adjusted. Since all detections are now conditioned on a detection at the new trigger detector, all probabilities are also conditioned on this detection, and the new heralded $g_h^{(2)}(0)$ value

$$g_h^{(2)}(0) = \frac{P_{t12}}{P_{t1}P_{t2}} \tag{2.5}$$

can be computed. In the heralded case, the probabilities can be expressed by the number of triple coincidence counts N_{t12} and the double coincidences N_{t1} and N_{t2}, normalized by the number of trigger events N_t: $P_{t1,2} = \frac{N_{t1,2}}{N_t}$. With that, it is

$$g_h^{(2)}(0) = \frac{N_{t12} \cdot N_t}{N_{t1} \cdot N_{t2}} . \tag{2.6}$$

Here, N_{t12} are the triple coincidences (both signal detectors, as well as the trigger detector register a photon), N_t is the single count rate of the trigger channel and $N_{t1,2}$ are the respective double coincidences. Please note that both the expression for the single beam $g^{(2)}(0)$ value eq. (2.4) and the heralded $g_h^{(2)}(0)$ value eq. (2.6) are independent of any detection efficiencies since both the numerator and the denominator depend on them in the same way. This is one of the reasons a $g^{(2)}(0)$-value less than 1 was one of the first experimentally shown quantum field effect, since it can be observed with low efficiency detectors.

2.1.2 Realization with the quED

Necessary Components

- quED setup with quCR
- quED-HBT Beam splitter
- quED-HBT detector

Experimental description

As in Fig. 2.3, one output of the quED is directly connected to one of the detectors. The other output is connected to the fiber beam splitter. Both of the beam splitter outputs are lead to the two remaining detectors. Three signals are measured now:

- Trigger photon: one arm of the quED directly (0)
- The second arm after the first output of the beam splitter (1)
- The second output of the beam splitter (2)

In the countrate tab of the quCR, we can now measure all count rates necessary to calculate both the $g^{(2)}(0)$ and the heralded $g_h^{(2)}(0)$ value. The only additional information needed is the duration of the coincidence window. This time window can be set in the *special parameters* tab in the expert mode of the software and is $t_c = 20\,\text{ns}$ by default. If you are using an older software version (< 5300), the coincidence window will be fixed at $t_c = 30\,\text{ns}$.

Measurement example

You can see an example measurement of the values needed for the normal $g^{(2)}(0)$ value in Fig. 2.4. For the heralded case, see Fig. 2.5.

2.1.3 Didactic Material

1. Calculate the $g^{(2)}(0)$ value for the not heralded case. What does the outcome mean?
2. How can the absence of triple coincidences be explained in the heralded case?

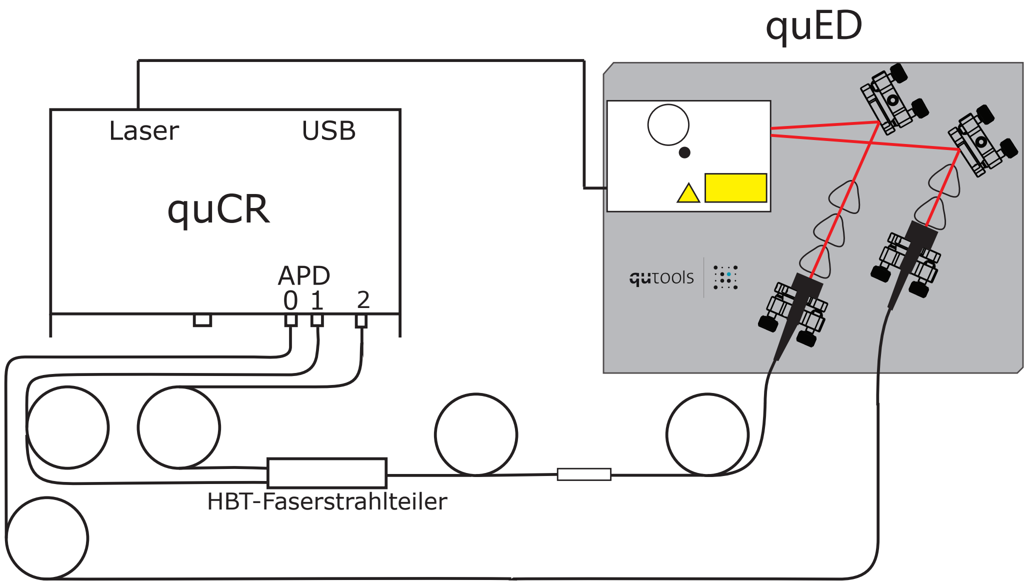

Figure 2.3: Schematic setup of the HBT-Experiment.

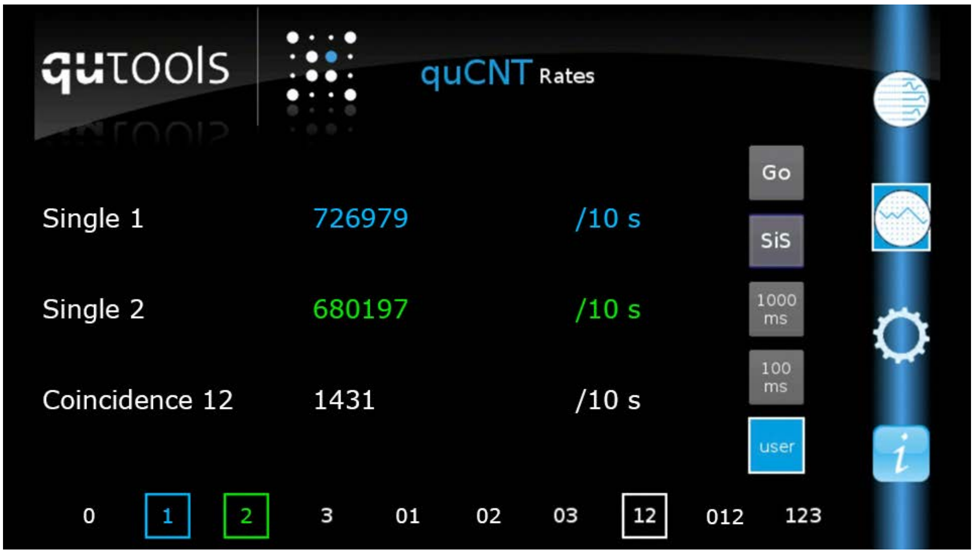

Figure 2.4: Example measurement of the HBT experiment for the $g^{(2)}(0)$ value with the quED.

3. Calculate the $g^{(2)}(0)$ value for a random and independent photon emission in both arms and for the numbers obtained in the actual experiment. **Hint:** The Poisson distribution is given by

$$P_\lambda(k) = \frac{\lambda^k}{k!}\,\mathrm{e}^{-\lambda} \tag{2.7}$$

where you can use the average photon number per coincidence interval for λ. Use a

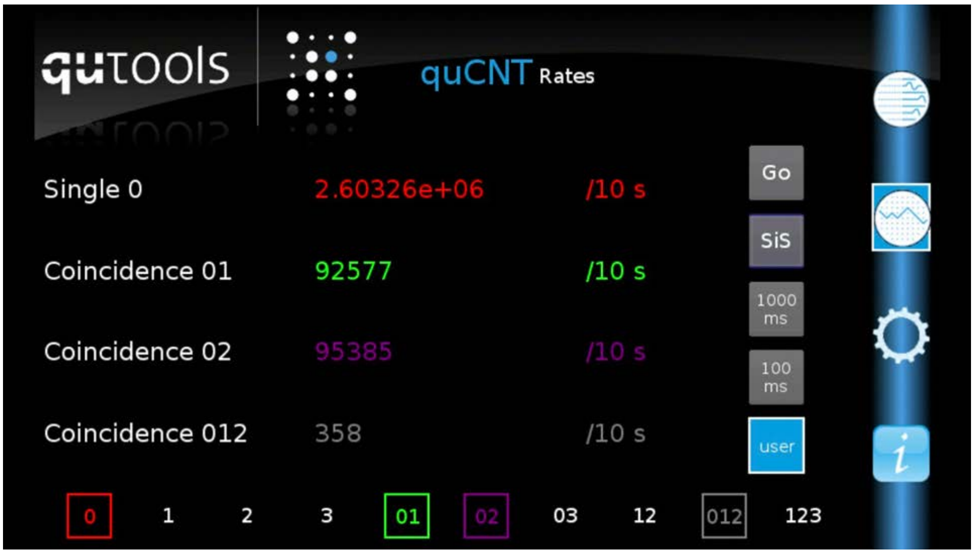

Figure 2.5: Example measurement of the HBT experiment for the heralded $g_h^{(2)}(0)$ value with the quED.

Taylor expansion for small λ ($e^{-\lambda} \approx 1 - \lambda + \lambda^2/2 - \dots$) and ignore terms of third order in λ.

4. What is the meaning of a $g^{(2)}(0)$ value significantly larger than 1?

2.1.4 Sample Solution

For the sample solution please refer to the qutools quED-HBT page `http://qutools.com/quED-HBT`.

Bibliography

[1] R Hanbury Brown and Richard Q Twiss. Correlation between photons in two coherent beams of light. *Nature*, 177(4497):27–29, 1956.

[2] John F Clauser. Experimental distinction between the quantum and classical field-theoretic predictions for the photoelectric effect. *Physical Review D*, 9(4):853, 1974.

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[4] Anton Zeilinger, Gregor Weihs, Thomas Jennewein, and Markus Aspelmeyer. Happy centenary, photon. *Nature*, 433(7023):230–238, 2005.