Pheno-Photonics

Experiments with SPDC Type-I generated single photons and phenomenology

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CHAPTER 1

Introduction

Ever since the development of modern theories in physics that challenge the metaphysical framework of what is known to us as classical, there has been an at times fruitful, at times difficult exchange between physicists and philosophers. It does, however, only happen rarely that one gets the chance to work in both fields at the same time — even less common being the combined work within experimental physics and theoretical philosophy. For this thesis, I have been given the opportunity to do exactly that, in regard to the especially interesting field of quantum phenomena.

This work will therefore consist of two parts: In the first half, I will describe working with the Thorlabs Quantum Optics kit EDU-QOP1(/M) that suggests a number of influential experiments performed with single photons which overall give a good overview of the fundamental and specific features of quantum mechanics. Namely, these experiments are

- the **Grangier-Roger-Aspect experiment**, which demonstrates the non-classical behavior of single photons by examining their interactions with a beam splitter,
- investigations of single-photon behavior in a **Michelson Interferometer**, providing evidence for the so-called "wave-particle duality" of photons through the observation of interference patterns, and showing how introducing which-path markers can erase such interference effects, as in a **Quantum Eraser** setup,
- and a straightforward (though not loophole-free) **Bell test**, offering strong evidence for entanglement and illustrating phenomena that cannot be explained by classical notions of locality.

Furthermore, this first part will include a discussion of the single-photon detectors with respect to their afterpulsing.

In the second half of my thesis, I will begin by motivating the relevance of philosophical debates regarding quantum mechanics through the notion of reality as a framework for the practice of physics. As an illustration, I will use passages from the famous EPR-paper. Furthermore, I will formulate two criteria for philosophical approaches to physics by rejecting anti-realist positions and defending a pluralistic form of realism concerning physics and other sciences that investigate potentially "real" entities. My main argument for these restrictions is based on a notion of interdisciplinarity that demands a basic respect for the practices of the other discipline involved.

As a philosophical framework that could hold up to these criteria and still provide interesting results when applied to physical concepts, I will suggest phenomenology. Instead of ascribing to a specific phenomenological tradition, I will formulate four distinguishing characteristics that I believe to provide the basis to use phenomenology as a method for the purposes of philosophy of science. I will then show that attempts to approach quantum mechanics phenomenologically have been made in the past, using the example of the French-Bauer-London approach to the measurement problem. I will discuss whether this approach lives up to my criteria for philosophical approaches, namely whether it is compatible with a realist account of physics and whether it does not end up in a form of subjectivism. Lastly, I deepen the discussion surrounding the role of the observer in quantum theory by pointing out particularities of the quantum mechanical measurement process based on the single-photon source used in Part I. This will eventually lead me to the idea of a type of experience that is particular to (quantum) experiments and that we can relate to physics as a mode of being. Finally, I will bring the results of both parts together in a concluding discussion.

Part I

Part I

CHAPTER 2

Single photons

A fundamental realization leading to the development of quantum mechanics has been the discovery that light is quantized in energy bundles today commonly known as photons [1, 617ff] This discovery led the way to the prediction and experimental verification of types of light that behave in ways no longer encaptured by former optical theories. When trying to understand what distinguishes quantum mechanics from other descriptions of reality in physics, light in such non-classical states is of special interest to us as it illustrates the particularities of the theory. In this thesis, the state of interest is the so-called single photon state, meaning a Fock state in which the average number of measured photons is equal to one [2, 49].

In this chapter, I will briefly introduce the formalism to describe such single-photon states and differentiate them from classical states, thereby defining the features that will further be explored experimentally in Chapter 3. Furthermore, I will introduce a type of Single Photon Source (SPS) which takes advantage of a non-linear optical process called Spontaneous Parametric Down-Conversion (SPDC). This type of SPS is of special interest to us as it will be used as a basis for the experiments to follow. I will give an overview on how it was practically implemented in the final section of this chapter and briefly characterize its output.

2.1 The single photon state

It is generally thought to be understood nowadays that light is composed of photons. While this understanding is helpful insofar as it captures the quantized nature of light, it seems helpful to take a closer look at what this quantization entails in order to understand the meaning of speaking of "single-photon states" or single photons in general.

Light is electromagnetic radiation. We can describe one mode k of its electric field similarly to a harmonic oscillator using a Hamiltonian of the form

$$\hat{H} = \hbar\omega(\hat{n} + \frac{1}{2}) \tag{2.1}$$

with the number operator $\hat{n}$. Applying this Hamiltonian to an energy eigenstate $|n\rangle$ of the mode k, we receive the energy eigenvalue of that state

$$\hat{H}\,|n\rangle = E_n\,|n\rangle = \hbar\omega(n + \frac{1}{2})\,|n\rangle \tag{2.2}$$

with $n = 0, 1, 2, \ldots$ [3, 12ff]. As we can see from Eq. 2.2, it is actually the energy of the mode k that is quantized, and we could e.g. understand n as the number of excitations of this mode. Alternatively, we could interpret an excited mode as a collection of energy bundles with a respective energy of $\hbar\omega$ each, meaning that n would denote the number of such bundles. Assuming that these individual bundles are called photons, the operator $\hat{n}$ would then be number operator that gives to us the average number of photons present in a state $|\psi\rangle$. The addition "average" is added here since light does not only occur in eigenstates of this operator, otherwise also known as number or Fock states. It therefore seems reasonable to look at different types of light in regard to their average photon number n and its variance over several measurements:

- **Thermal light**, being the most common type of light in our everyday world, is characterized by large intensity fluctuations. The probability to find n photons in mode k is given by

$$\mathrm{P}_k(n) = \frac{\langle n\rangle^n}{(1 + \langle n\rangle)^{n+1}}$$

  with $\langle n\rangle$ being the average photon number this mode. Looking at this distribution, we realize that the most likely outcome is actually to find zero photons in any given modes. At the same time, the variance of the average number of photons over several measurements, given by $\Delta n^2 = \langle n\rangle^2 + \langle n\rangle$, is large compared e.g. to a Poissonian distribution. Due to this fact, we can say that the photon statistics of this light present as Super-Poissonian.

- **Coherent light** is a more ordered type of light, commonly associated with lasers. Coherent light can be described by a linear combination of Fock-states:

$$|\alpha\rangle = e^{-\frac{|\alpha|^2}{2}} \sum_{n=0}^{\infty} \left(\frac{\alpha^n}{\sqrt{n!}} \cdot |n\rangle \right).$$

  We then find that

$$\mathrm{P}_l(n) = \frac{\langle n\rangle^n}{n!} \cdot \exp^{-\langle n\rangle}$$

  with $\langle n\rangle = |\alpha|^2 = \Delta n^2$ meaning that variance is equal to the average photon number. The most probable outcome is then to find $\langle n\rangle$ photons in a given mode, which is different from the most probable zero photon state of thermal light. We therefore also call this light Poissonian, since its variance corresponds to the variance of a Poissonian distribution.

- Finally, the **single photon state** $|1\rangle$ can be understood as the very first excited Fock state. Its expected photon number is therefore $\langle n\rangle = 1$ with a variance of $\Delta n = 0$ since as a Fock state, it is an eigenstate of the number operator $\hat{n}$. Due to this, the single photon state (as well as all other number states or Fock states $|n\rangle$) can be considered as light with a Sub-Poissonian probability distribution.

The formulas given and further details can for example be found in Lounis and Orrit [4] or in standard optics textbooks such as Fox [5, Chapter 5].

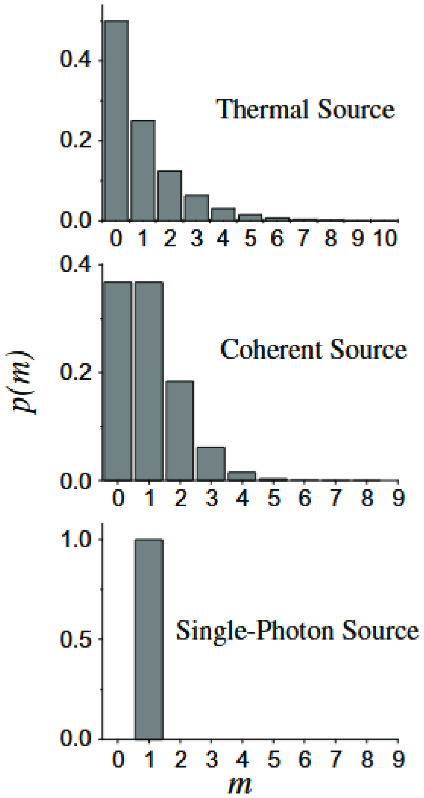


Figure 2.1: Probability distribution of the photon number for different light source, all with an average number of photons of $\langle n \rangle = 1$, displaying the differences between Super-Poissonian, Poissonian and Sub-Poissonian photon statistics – graphics taken from [4, 1135].

A visualization of these different states of the electromagnetic field in terms of their photon number statistics can be found in Fig. 2.1. In reality, the production of coherent as well as single-photon states in the lab is never perfect, resulting in the need of a value that can characterize the quality of e.g. a single photon state. Usually, for this the second-order correlation function

$$g^{(2)}(\tau) = \frac{\langle \bar{I}(t)\bar{I}(t+\tau) \rangle}{\bar{I}^2} = \frac{\langle E^*(t)E^*(t+\tau)E(t)E(t+\tau) \rangle}{\langle E^*(t)E(t) \langle^2} \tag{2.3}$$

is used, with $\bar{I}$ being the average intensity measured at t, E the e-field to which this intensity is proportional and τ being a chosen time-delay between two moments of measurement [6, 106]. Without going into the specifics of its derivation from the expression of the respective states (for this, see for example Loudon [6, 219ff]), we can say that

- for **thermal light** $g^{(2)}(0)$ approaches 2,
- for **coherent light**, such as laser light, $g^{(2)}(0)$ it is 1 (symbolizing uncorrelated photon emissions)
- and thirdly, for **non-classical light** in Sub-Poissonian states (such as the single photon state),

$g^{(2)}(0) < 1$ which suggest anti-correlation of the photon signals.

The value of $g^{(2)}(0)$ can be measured e.g. by observing the behavior of light on a beam splitter, as we will see in Sec. 3.1. This way, the second-order correlation function can be used to characterize the quality of our SPS and confirm the fact that non-classical states of light are used in the experiments in Ch. 3

2.2 Spontaneous parametric down-conversion and single photon sources

There has been a rising demand for light sources that emit light in the afore described single-photons state ever since the 1980s, amplified by the growing interest in quantum telecommunication [7, 8]. One of the earliest types of such SPS takes advantage of the correlated creation of two photons. These bi-photon sources can be used to create near-single photons states by using one of the photons as a heralding signal for the second photon, usually called the signal photon. By only counting heralded clicks on the signal channel, we therefore try to select for photons that appear individually and are not the result of multiple-pair generation typical for classical light sources. For such sources, single atoms or nonlinear crystals present themselves as natural choices [8, 13].

Another way (and maybe more "quantum" way) of describing this process of selection employed in heralded SPS is by understanding heralding as a projection onto the desired pure single photon state. To understand this idea, we should focus on the specific process of bi-photon production that is used in the case of SPDC-based single photon sources. Parametric down-conversion describes the creation of two photons with the respective frequencies ω_s and ω_t from a pump photon with the frequency ω_p based on its interaction with a non-linear optical medium. In this process, the strong pump field interacts with the nonlinear medium through its nonlinear susceptibility. This interaction gives rise to a phenomenon in which a pump photon is spontaneously converted into a pair of lower-energy photons, commonly referred to as the signal and idler. For the created photons, energy conservation demands that

$$\omega_p = \omega_s + \omega_i, \tag{2.4}$$

justifying the name "down-conversion" as the frequency of the two produced photons is lower than the frequencies of the stimulating photon. *Symmetric* SPDC describes the case in which $\omega_s = \omega_i$.

Due to dispersion, the refractive index depends on the frequency of the light interacting with the medium. In the case of SPS, we are therefore confronted with a refractive index n_p for the pump photon that is different from the refractive index $n_i = n_s$ for the two emitted photons of the same frequency. This is desirable to us, as the different indices for the pump and emitted photons help to fulfill the second condition of the creation of signal and idler photon which is known as phase-matching, meaning that

$$\vec{k}_p = \vec{k}_s + \vec{k}_i \tag{2.5}$$

with $\vec{k}_p$, $\vec{k}_s$ and $\vec{k}_i$ being the wave vectors of pump, signal and idler photon respectively [9, 436].

Following Lvovsky et al. [10], we can now describe the emitted state resulting from SPDC in a birefringent crystal as

$$|\psi\rangle = N \cdot (|0,0\rangle + \int \mathrm{d}\vec{k}_s \mathrm{d}\vec{k}_i \, \Phi(\vec{k}_s, \vec{k}_i) \, |1,1\rangle) \tag{2.6}$$

with N being a normalization factor and $\Phi(\vec{k}_s, \vec{k}_i)$ the function defining the amplitude and spatial structure of the resulting bi-photon state. If we now measure an idler photon, represented itself as an ensemble of possible states $\hat{\rho}_i = \int \mathrm{d}\,\vec{k}_i\, T(\vec{k}_i)\, |1_{\vec{k}_i}\rangle \langle 1_{\vec{k}_i}|$, we project the original state $|\psi\rangle$ onto a state ensemble

$$\hat{\rho}_s = \mathrm{Tr}_i[|\psi\rangle \langle\psi|\, \hat{\rho}_i] \tag{2.7}$$

where Tr_i indicates the partial trace with respect to the idler photon. The state ensemble $\hat{\rho}_s$ approaches a single-photon state when the transmission function $T(\vec{k}_i)$ is sufficiently narrow. This transmission function is defined by the filtering of the idler photon happening before its detection (in the case of the setup in this thesis it is e.g. realized using a band pass filter and an iris implemented into the detector optics). All this is to say that while the measurement of the idler photon can be understood as a selection of measurement data in a classical sense, within the formalism of quantum mechanics it is more accurate to understand it as transformation of the initial state through measurement (that is via a projection onto the measured states), thereby only creating the near single-photon state through this process.

Despite the fact that through this mechanism, states close to single-photon states can be produced, we can also use it for the creation of polarization entangled photons. To understand this, it is relevant to take a brief look at the polarization of the produced photon pairs: In the case of SPDC Type I, the phase matching condition (Eq. 2.5) is met by a parallel polarization of signal and idler photon that is orthogonal to the polarization of the pump laser and the optical axis of the crystal [11, 34]. By now combining two of these non-linear crystals with perpendicular optical axes, we can create polarization-entangled photons in the state

$$|\Psi\rangle = \frac{|HH\rangle + e^{i\delta}\,|VV\rangle}{\sqrt{2}} \tag{2.8}$$

with the relative phase δ since the exact location of creation (in crystal 1 or crystal 2) is not verifiable and can only be determined through measurement [12, 620]. It should be noted that this state is only to be found at the intersection of the two cones produced by the two crystals used. As it corresponds to the Bell state Φ^+, it can, be used to perform Bell tests, as we will see in Sec. 3.4.

2.3 Implementing a single photon source

In this thesis, single photons were produced using a β-BBO-crystal, in which SPDC Type I can occur. A schematic of the actual setup of the SPS can be seen in Fig. 2.2. The components and the arrangement of the SPS are both taken from the Thorlabs Quantum Optics Educational Kit EDU-QOP1/M. The pump laser included in the kit has a wavelength of 405 nm, leading to the emission of a signal and an idler photon at 810 nm each in the degenerate case. Of course, the actual wave length of either produced photon can vary according to Eq. 2.4, leading to a statistical distribution of wavelengths in the cone [9, 437].

As we can see in Fig. 2.2, the pump laser first passes a half-wave plate set to 45° which is intended to turn the polarization of the pump laser beam so that it experiences the extraordinary refractive index of the crystal, as required for Type-I phase matching (meaning in order to fulfill Eq. 2.4 and Eq. 2.5). Then, the pump laser is sent aligned through the BBO-crystal. After the crystal, the generated photon pairs propagate along a cone, out of which a limited cutout on opposite sides of the cone is then detected by single-photon sensitive photon detectors. A band pass filter with a central wavelength of 810 nm and a FWHM of 10 nm was integrated directly into the detector

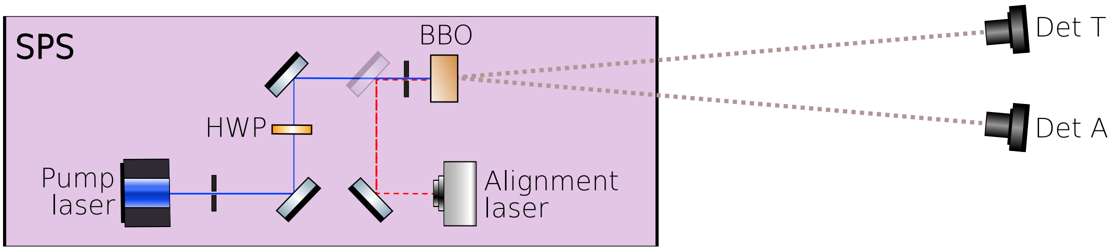


Figure 2.2: Schematic of the SPS used in this thesis, pictured with a single BBO-crystal (3 mm, $\theta = 29.2°$), optical axis set to 0°, half-wave plate (HWP) set to 45°.

optics in order to limit the detectable photons further to the photons created in Symmetric SPDC (and filter out e.g. the photons of the blue pump laser beam). The laser included in the kit is a diode laser with a maximal power of about 25 mW. A characterization of its laser power can be found in the appendix as Figure A.1.

A difficulty in the alignment process is posed by the fact that the single photons emitted by the source are neither visible nor detectable by means other than the single-photon detectors. Furthermore, they are not emitted in a straight line. The kit therefore includes an alignment laser visible to the human eye and an axicon with a 3° opening angle, mimicking the shape of the cone created by the SPDC, which can be used to replace the BBO crystal after inserting the mirror pictured as transparent in Fig. 2.2.

Applying a pump laser power of about 13 mW, count rates of about 500 kHz to 700 kHz on both Detector T and Detector A could be achieved, with the coincidence rate between these two signals turning out to be about 30 kHz when measured with a coincidence window of 5 ns. A bidirectional histogram of these time differences between counts on Detector T and A is pictured in Fig. 2.3. The fact, that the contribution is not completely centered indicates a delay in one of the signals either because of a difference in path length or a difference in the processing speed. Since we know that the source produces true coincidences, this delay was compensated in the following measurements by introducing an offset to one of the signals determined by the position of the maximum of the contribution. Since the setup was changed and optimized a few times between the different measurements and experiments, this delay varied and was therefore re-calculated for every dataset. It, however, remained within a range of 1 to 3 ns.

All measurements in this thesis (unless stated otherwise) were performed using single photon detectors with adjustable gain (*SPDMA* by Thorlabs). According to the manufacturer, they are supposed to offer a detection efficiency of 43% at 820 nm and their dark count rates are supposed to lie between 300 and 1 500 Hz at maximum gain. These and other parameters (such as the dead time) can vary for the specific detectors used which is why a short characterization of the different detectors used is included in the appendix (A.1.2). All detectors used were operated at maximal gain as it was suggested by Thorlabs [11].

The single photon detectors turn the detected photons into an electric pulse which is passed on to a *TimeTagger 20* by Swabian Instruments. Some more details of the workings of detectors and the discussion of the pulse shape will follow in Sec. 3.2. Either way, the TimeTagger provides every signal with a certain falling or rising edge (this can be specified during usage) with a time tag, making it possible to turn the individual detection events into count rates or bin them e.g. into histograms

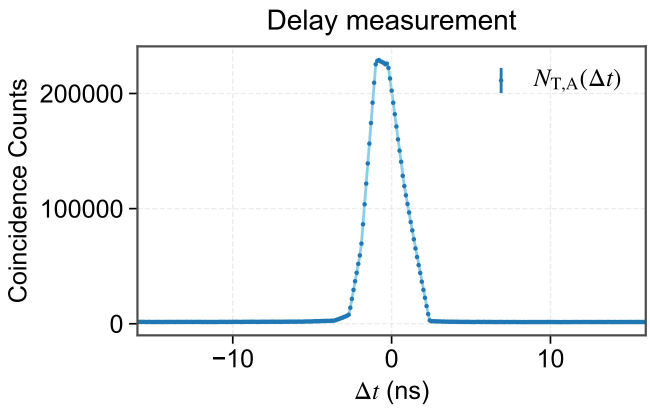


Figure 2.3: Correlation-histogram of the signals of Detector T and Detectors A. Measurement was taken for 100 s with a 50:50-beamsplitter already installed in the arm of the SPS leading to Detector A, thereby reducing the overall count-rates. A slight time difference of about 1 ns is clearly visible between the two signals of the SPS.

displaying the time differences between different signals. As the TimeTagger has several inputs, the same can be done for signals coming from different sources (e.g. several single photon detectors), making it possible to perform coincidence measurements which will be of special interest for most experiments performed in this thesis. In order to work with the data provided by the TimeTagger, the python library `Timetagger` provided by Swabian Instruments was used.

CHAPTER 3

Experiments with single photons

Experiments involving single photons have become increasingly accessible thanks to the development of laser technology. Thanks to these technological advances in optics, experiments that were once extremely difficult to set up and therefore bound to highly specialized research laboratories are now available for commercial use or in educational settings to be performed by students. In this thesis, I work with such a kit, namely the Thorlabs Quantum Optics Educational Kit EDU-QOP1/M, to perform and analyze experiments at the single-photon level which provide a solid basis for an understanding of quantum phenomena.

These experiments explore some of the fundamental characteristics of light in single-photon states (in the following section also occasionally simply called "single photons")[1]. The basis of all of these experiments is the SPS as described in Sec. 2.3. Using it, I will first show that the produced photons are indeed in the single-photon regime, confirmed by their anti-correlative features beyond the classical limit of $g^{(2)} > 1$. For this, their behavior on a beam splitter as well as the behavior of light stemming from other light sources was observed and analyzed in regard to the second-order correlation function, as described in Sec. 3.1. While performing these first experiments with the kit, ringing effects from the single-photon detectors showed up in the measurement data. These effects and their cause will be further explored in Sec. 3.2. In Sec. 3.3, I will investigate single photon interference using a Michelson-interferometer and show the influence of introducing three polarizers into the different interferometer arms, thereby creating a Quantum Eraser. Subsequently, after having changed the crystal used in my SPS to a Barium Borate (BBO)-crystal pair, I will show in Sec. 3.4 how this setup can be used to perform simple Bell tests that violate the CHSH-inequality. Lastly, in Sec. 3.5, I will shortly summarize my experimental results and give an outlook on further possible explorations.

3.1 Different types of light on a beamsplitter

As we have seen in Sec. 2.1, different types of light can be distinguished by looking at their second-order correlation function $g^{(2)}$ measured at $\tau = 0$, meaning with no time delay. Experimentally, this

[1] This should not distract from the complex definition of what a photon could actually be or mean, as provided to some extent in Ch. 2. It is, however, a formulation commonly used in the literature and has therefore been adopted here for simplification.

measurement can be realized by dividing a beam of light coming from a given source on a beam splitter and then calculating $g^{(2)}$ using the detector signals measured after the beam splitter according to Eq. 2.3. Since in this thesis, single photon detectors were used, it is necessary to exchange the expression of the average intensities used in Eq. 2.3 by an equivalent using count rates. While the Thorlabs kit manual does provide a short derivation of such an expression, the code that was used in this thesis to calculate $g^{(2)}(\tau)$ is based on the calculations by Signorini and Pavesi [13] who ultimately arrive at the expression

$$g_{\mathrm{h}}^{(2)}(\Delta t) = \frac{R_{ssi}(\Delta t)}{R_{si}^{(1)}(t)R_{si}^{(2)}(\Delta t)}R_i(t) \tag{3.1}$$

for a heralded SPS. Here, $R_{ssi}(\Delta t)$ represents the temporal distribution between the idler photon and the two outputs of the beam splitter, $R_{si}^{(2)}(\Delta t)$ the temporal distribution of beam splitter output 2 and idler photon, $R_{si}^{(1)}(t)$ the double coincidence rate between the idler photon and beam splitter output 2 at the time t and $R_i(t)$ simply the count rate of the idler-detector at time t as well.[2] Special attention should be paid once more to the different time markers used: While Δt should be understood similarly to τ in the former expressions of the $g^{(2)}$-function, meaning as a time difference between the signals of two or more detectors, t simply stands for the absolute moment in time at which the measurement was taken, thereby accounting for possible fluctuations in intensity of the source over time.

The exact setup used to measure these coincidence and count rates is pictured in Fig. 3.1. This experiment is known as the Grangier-Roger-Aspect-experiment and is commonly used to test the quality of single photon sources. I will first discuss the results using the SPS (Sec. 3.1.1) and then compare it to the results when using a classical light source in Sec. 3.1.2.

3.1.1 Grangier-Roger-Aspect experiment

With the setup pictured in Fig. 3.1, the Grangier-Roger-Aspect (GRA)-experiment was performed and once evaluated using the kit software (meaning that the $g^{(2)}$-function was automatically calculated by the software written by Thorlabs) and then repeated to calculate the $g^{(2)}$-function directly from the raw data of the TimeTagger. The results of the kit software are pictured in Fig. 3.2a), with the approach of the kit software being to calculate $g_h^{(2)}(0)$ at different moments of time and then display them as a continuous graph. Sadly, the exact formula used for this graph is not mentioned in the documentation of the kit.[3] It is therefore difficult to estimate an error the values given which is why the plot in Fig. 3.2a is pictured without error bars. This should, however, not suggest that the values are actually errorless especially as they were calculated using data of imperfect measurement devices.

For the analysis of the data directly recorded by the TimeTagger, the entire $g_{\mathrm{h}}^{(2)}(\Delta t)$-function was calculated to highlight the typical “dip” at $g_{\mathrm{h}}^{(2)}(0)$. The results can be seen in Fig. 3.3, one graph showing a larger and one a smaller Δt-range. The error sources for the values displayed are manifold: For once, the detectors do not have a perfect detection efficiency (especially not at the wavelength used as it was briefly discussed in Sec. 2.3). TThis means that for example from the two photons of a true coincidence event only a single one is detected, and therefore not registered as a coincidence in the recorded data. Since this is however the case for all detectors involved, this error can be assumed

[2] In Eq. 3.1, $R_{ssi}(\Delta t)$ and $R_{si}^{(2)}(\Delta t)$ are given as rates; however, since they are both normalized by the measurement duration, the number of events $N_{ssi}(\Delta t)$ and $N_{si}^{(2)}(\Delta t)$ can be used here just as well.

[3] While the kit does mention several different expressions for the $g^{(2)}$-function, the asymptotic course of the graph suggests that either the count and coincidence rates or the final $g^{(2)}(0)$-value are also somehow integrated.

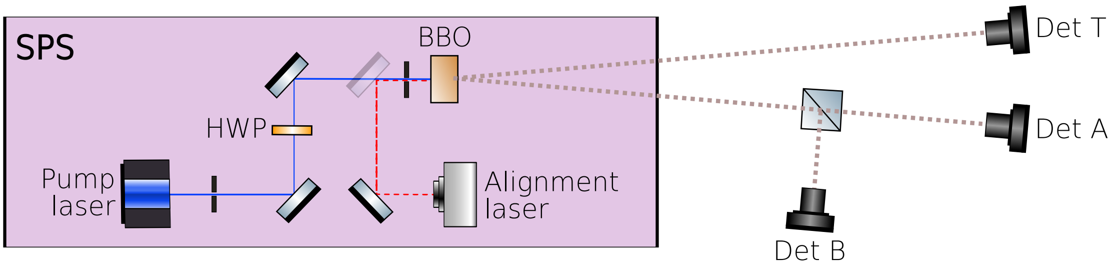


Figure 3.1: Schematic of the setup used to perform the GRA-experiment: The three detectors pictured are single photon detectors, with a bandpass filter for 810 nm, FWHM=10 nm included in the detector optics, all detectors are connected to a TimeTagger; the pictured beamsplitter is a non-polarizing 50:50-beamsplitter, anti-relection coated for 700 to 800 nm.

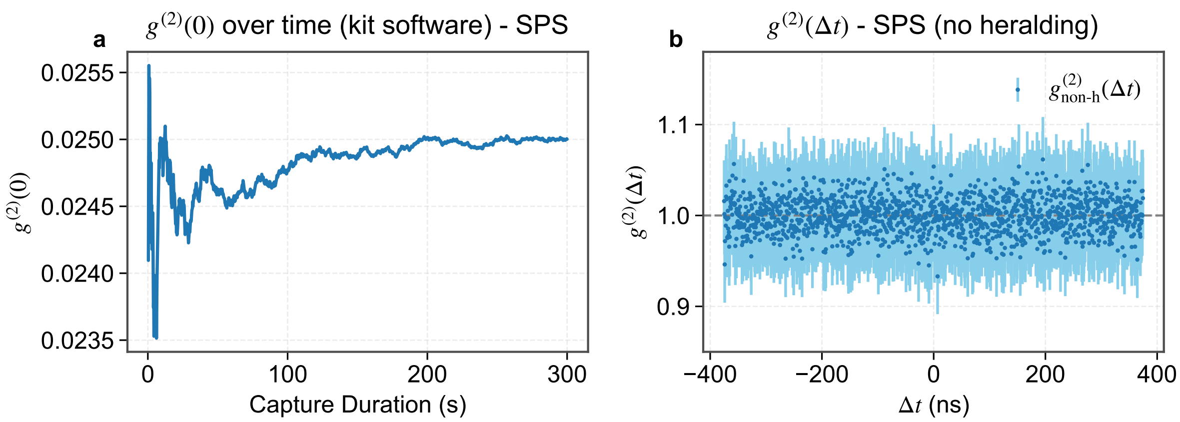


Figure 3.2: **a)** Time evolution of the zero-delay second order correlation $g^{(2)}(0)$ of the SPS (GRA-experiment), measured with the kit software for 300 s. The software calculates $g^{(2)}(0)$ automatically using a triple coincidence scheme; **b)** $g^{(2)}(\Delta t)$ of the heralded SPS, calculated using Eq. 3.5 without considering the heralding effect using the same measurement data as used in Fig. 3.3. The graph shows that the typical dip at $g^{(2)}$ disappears when the heralding of the source is not considered.

to reduce all count and coincidence rates by a similar factor (for coincidence rates, this factor is obviously higher), meaning that it will not be of greater relevance for the error on the $g^{(2)}$-function.

On top of that, there could be false coincidences caused by unrelated photon events randomly occurring within in the defined coincidence window. The rate at which this form of false coincidences can be assumed to happen for a coincidence measurement between two signals 1 and 2 is given by

$$R_{\text{acc, 12}} = 2 \cdot R_1 R_2 \tau \tag{3.2}$$

with τ being the coincidence value that defines the resolution of the coincidence rate and $R_{1/2}$ the count rates of the two counters used [14]. For a threefold coincidence, this formula extents to

$$R_{\text{acc, 123}} = 3 \cdot R_1 R_2 R_3 \tau^2. \tag{3.3}$$

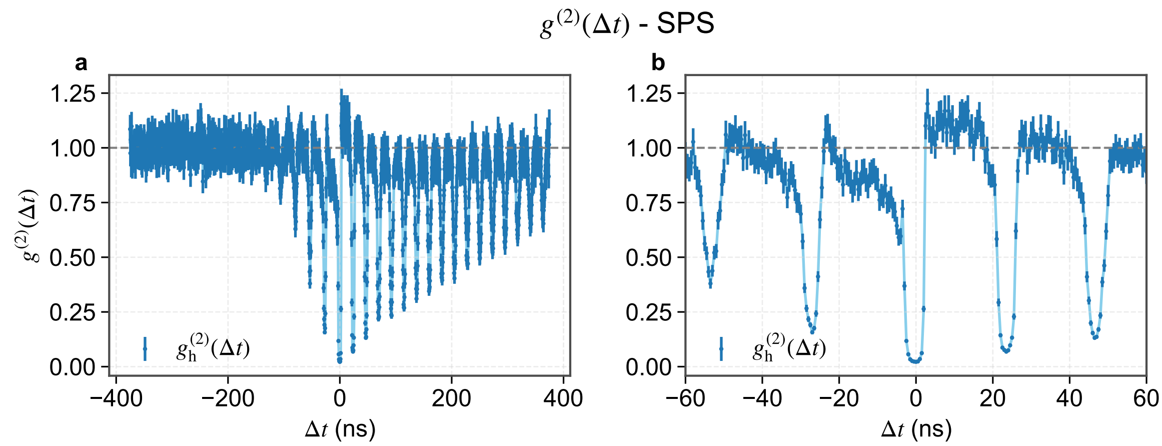


Figure 3.3: $g^{(2)}(\Delta t)$ of the heralded SPS, calculated using Eq. 3.1 with a coincidence window of 5 ns, measured for 100 s: **a)** displaying a larger area of the function from −400 ns to 400 ns, **b)** showing a smaller clipping of the area between −60 ns to 60 ns. The typical dip at $g^{(2)}$ shows that the source does in fact produces single photons that superceed the classical limit of $g^{(2)}(0) > 1$.

In this thesis, mainly double coincidence rates were used, and the count rates in the experiments were between 100 to 800 kHz. Assuming that both rates are at their maximum of $R_1 = R_2 = 800$ kHz, the maximal rate of accidental coincidences would then be $R_{\mathrm{acc},12} = 3\,200$ Hz for a coincidence window of 5 ns. However, usually at least one of the count rates is lower than this upper limit and therefore, the error coming from accidental coincidences can be expected to remain beneath this limit. We can see from this that the error is at least two orders of magnitude than the relevant values for the coincidence rates — hence, it should not influence the credibility of our results.

Yet another error source is the TimeTagger. Since the association of time stamps to detection events provided by the TimeTagger is not perfect, small deviations from the actual detection order or timescale will be introduced, generally known as time-jitter. According to the manufacturer, the FWHM of the jitter comes down to 80 ps [15]. For our application with a coincidence window of 5 ns, this error seems negligible in comparison to the other error sources. For regular coincidence rates such as $R_{si}^{(1)}(t)$, the same can be assumed for false coincidences caused by dark counts as the rate of accidental coincidences given by Eq. 3.2 supersedes errors just caused by dark counts by far (for proof, see the coincidence measurements caused by dark counts in the appendix, Fig. A.4, or calculate the accidental coincidences that would be caused by replacing one of the rates in Eq. 3.2 by the dark count rate).

The distributions $N_{ssi}(\Delta t)$ and $N_{si}^{(2)}(\Delta t)$ can be considered to be histograms: Data is binned depending on the time delay detected between the signals involved. Generally, each of these data points can therefore be understood to possess Poissonian statistics and can be assigned an inherent standard deviation of $\sqrt{N}$ [16, 37] (shot noise). This assumed error is rather large in comparison to the accidental coincidences that could be caused by dark counts within in the individual beams considering that these accidental coincidences would be evenly spread over the entire histogram (dark counts are generally not correlated unless they fall under the definition of detector ringing as explained in Sec. 3.2).

Finally, for single count rates such as $R_i(t)$, we can assume that dark counts and stray photons are in fact the biggest sources of error. Throughout this thesis, it will simply be assumed to be the error on any singular count rate unless stated otherwise. The error of the overall $g^{(2)}$-function can then be calculated via standard error propagation, considering all these different sources of errors on its components.

It should be mentioned that the recorded values for $g^{(2)}(\Delta t)$ at $\Delta t = 0$ differ slightly between the kit and the value using Eq. 3.1 (even when accounting for the error on the latter), suggesting once more a different mathematical approach by the kit software: The dip in the data analysis of the raw data recorded by the TimeTagger comes down to value of $g^{(2)}_{\text{raw}}(0) = 0.0221 \pm 0.0010$ while the value calculated by the kit software seems to approach a value rather close to $g^{(2)}_{\text{kit}}(0) = 0.025$. Due to the afore mentioned lacking documentation of the exact calculations performed by the kit software, this slight deviation cannot be fully explained here. One reason for it could be that the kit supposedly uses one-sided coincidences, while $g^{(2)}(\Delta t)$ in Fig. 3.3 was calculated using a double-sided coincidence scheme. Furthermore, the fact that the kit seems to somehow integrate the value for $g^{(2)}(0)$ over time most likely also leads to the pattern appearing in the first 50 s of the measurement. As once again, the way the $g^{(2)}$-function is integrated here is not mentioned in the manual, this pattern can not be interpreted further.

Nonetheless, both graphs confirm very clearly that the value of $g^{(2)}_h(0)$ is beneath the classical limit of $g^{(2)}(0) = 1$. We can understand this result as follows: The fact that the $g^{(2)}$-function is smaller than 1 here implies anti-correlation between the signal of Detector A and Detector B. When interpreting this behavior using classical term, we could say that this speaks to the photon's particle nature: While we would expect a wave to simply divide, photons in a true single photon state cannot be split, but instead always emerge in one output or the other — never in both simultaneously [17].

Further, the $g^{(2)}(0)$-value can be used as proof that the SPS does actually produce photons in the single-photon state. If we rewrite the $g^{(2)}$-function in terms of mean photon number $\bar{n}$ and its variance $V(n)$, we get to the expression

$$g^{(2)}(0) = 1 + \frac{V(n) - \bar{n}}{\bar{n}^2}. \tag{3.4}$$

This can be reduced to $g^{(2)}(0) = 1 - \frac{1}{n}$ for a number state $|n\rangle$ [18, 37]. Therefore, a value smaller than 1/2 can be seen as proof that not only, non-classical Fock states are present in the photon mixture detected (pushing the $g^{(2)}(0)$-value beneath 1) but also that a significant quota of these photons must be in the Fock state $|1\rangle$.

It should be pointed out that besides the characteristic dip at $\Delta t = 0$ in Fig. 3.3 we can spot some further structures (more "dips") to the right of the main dip at $\Delta t = 0$. These secondary dips will be further explored in Sec. 3.2.

Using these measurements, we can also visualize the importance of the idler photon for the state preparation by looking at its $g^{(2)}$-function. When treating the SPS as a source for which no heralding is required, the expression for the $g^{(2)}$-function changes to

$$g^{(2)}_{\text{non-h}}(\Delta t) = \frac{R_{AB}(\Delta t)}{R_A \cdot R_B \cdot \delta t} \tag{3.5}$$

with δt being the bin width of the correlation histogram given by $R_{AB}(\Delta t) \cdot$ (Measurement Duration) [11]. This $g^{(2)}$-function, ignoring the heralding effect of the idler photon, can be calculated for the data recorded by the TimeTagger of the same measurements as used for Fig. 3.3. The results of this re-calculation of $g^{(2)}(\Delta t)$ are displayed in Fig. 3.2b — as we can see, the $g^{(2)}$-function no longer dips at $\Delta t = 0$ and rather resembles the evenly distributed results of laser light as seen in Sec. 3.1.2. This difference should illustrate that heralding is precisely what allows the detected photons to qualify as non-classical, as reflected by $g^{(2)}(0) < 1$. The meaning of the special role of heralding, while the underlying physics is fully explained by projection formalism given in Chapter 2.1, will further be explored in Part II of this thesis.

3.1.2 Hanbury-Brown-Twiss experiment with classical light

To verify that the characteristics described in the previous section (in particular the dip of the $g_h^{(2)}$-function at $\Delta t = 0$) are particular to the SPS in use, the experiment was repeated using attenuated laser light with a final power of about 9 µW after the dimming. The laser beam was sent onto a 50/50-beamsplitter and two outputs were monitored with two single photon detectors (denoted as Detector A and Detector B). As a laser source, the weaker alignment laser was used in order to not overstrain the single photon detectors. Detector T was not used as this type of light does not require a heralding scheme. A schematic is not included here but can be found in the manual [11, 116]. The $g^{(2)}$-function for this experimental setup was as before calculated once using the kit software and once using raw data collected by the TimeTagger and Eq. 3.5. Both graphs are pictured in Fig. 3.4.

These results very clearly show that the value of $g^{(2)}(0)$ exceeds the values previously measured (for comparison, see Fig. 3.3 and Fig. 3.2a), lying rather close to or slightly above the classical limit of 1.[4] The results of both measurements therefore prove that attenuated laser light does not possess the anti-correlative features of light with sub-Poissonian statistics (indicated by $g^{(2)}(0) < 1$) and is therefore not suitable as a single-photon source. Instead, it behaves like a classical coherent state where photons arrive independently, such that coincident detections are not suppressed.

[4] There seems to be a slight dip at $\Delta t = 0$, however, when looking closely, the lower value pictured can actually be contributed to a value of Δt slightly above 0. We can therefore assume that this is simply a statistical fluctuation.

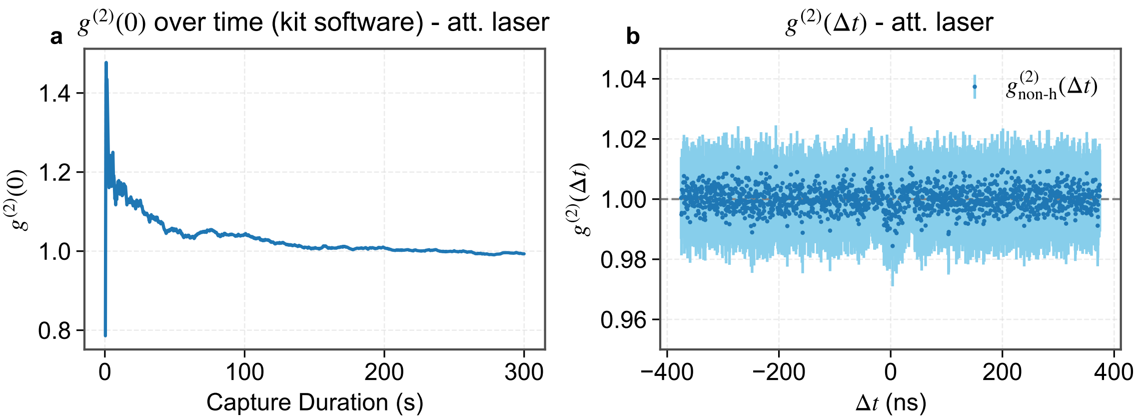


Figure 3.4: **a)** $g^{(2)}(\Delta t)$ of the dimmed alignment laser (HBT-experiment, using a 50:50 beam splitter), calculated using Eq. 3.5, the measurement duration was 300 s. The plot shows to be centered around $g^{(2)}(\Delta t) = 1$, showing no significant features that would suggest anti-correlative (non-classical) behavior of the photons measured, therefore disqualifying dimmed laser light as an SPS. **b)** Time evolution of the zero-delay second order correlation $g^{(2)}(0)$ of the alignment laser on an ND-filter in the GRA-experiment. The kit software calculates $g^{(2)}(0)$ automatically.

3.2 The detectors and detector ringing

During the measurements and analysis of the GRA-experiment, unexpected structures were observed in the $g^{(2)}$-function of the SPS. These features, illustrated in Fig. 3.3, exhibit a periodicity of approximately 22 ns. When interpreted within the framework of the $g^{(2)}$-function, they appear to indicate that there are further signals separated by delays of $n \cdot 22$ ns that display anti-correlative behavior, next to the simultaneously created photons that cause the characteristic dip at $\Delta t = 0$ ns. Since our source only produces single photons with strong temporal correlations, it seems unlikely that these secondary dips correspond to genuine emission events. Given the pronounced periodicity of these features, this observation suggests an electronics problem after the photon detection is converted into an electrical signal. intrinsic property of the single-photon detectors, such as detector ringing.

To understand, what detector ringing is and why it appears, it seems sensible to take a closer look at the actual processes appearing in the detectors used. The SPDMAs by Thorlabs function on the basis of a silicon avalanche photodiode. An Avalanche Photo Diode (APD) generally works like a normal photo diode, meaning that it can turn photons into an electric signal usually using the photoelectrical effect. However, it additionally possesses an internal amplifier using the avalanche effect [19, 20]. This effect appears at a p-n-junction when it is operated near or even slightly beyond its breakthrough-voltage, creating a high electrical field. If this diode is now stimulated by an external photon, the created free charge carriers, provided with a sufficiently high energy by the electric effect, start an avalanche of ionization, therefore leading to the automatic amplification of the initial signal.

Due to the fact that the diode is operated in his meta-stable state close to the breakthrough voltage, it is not unlikely that such amplification effects (avalanches) are not triggered by an external disturbance but instead appear spontaneously. Such spontaneously caused avalanches are the underlying cause of the so called dark counts (see Fig. A.2) [21]. Additionally, avalanches can be caused in the

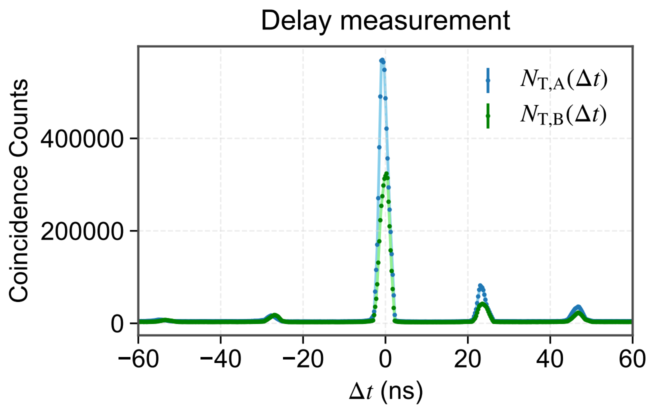


Figure 3.5: Correlation-histogram of the signals of Detector T and Detectors A and B respectively (data taken from the same measurement as Fig. 3.1). The equidistant second maxima suggest detector ringing as a cause for the secondary dips observed in the $g^{(2)}$-function (also Fig. 3.1).

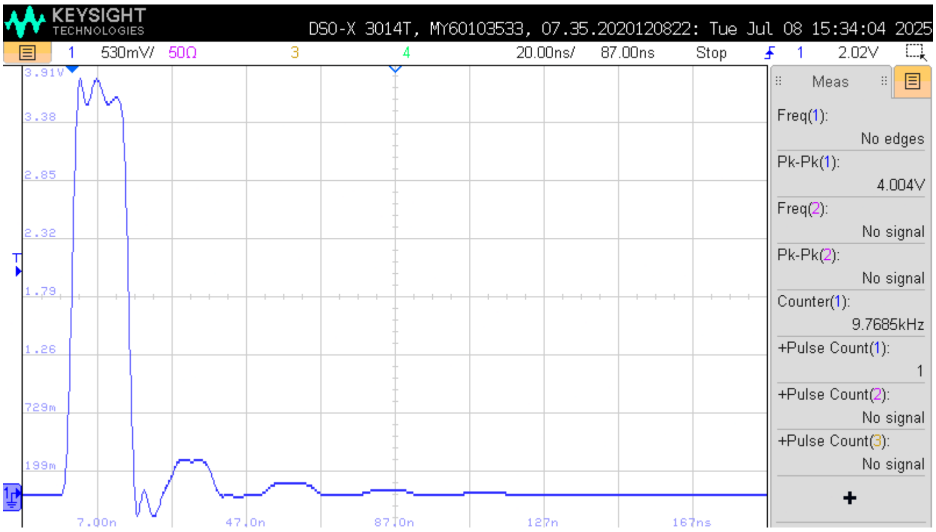
aftermath of "real" signals. This form of correlated noise is generally known to be caused by lingering charge carriers. If these free charge carriers are trapped long enough (meaning longer than the dead time of the detector), for example due to unintended energy levels caused by imperfections in the crystal pattern, they can cause secondary avalanches known as afterpulses [20]. When this happens repeatedly, these afterpulses appear as a form of ringing also known as "detector ringing".

It can be confirmed that the photon detectors used in this work display afterpulsing by examining their voltage output on an oscilloscope. Two representative traces are shown in Fig. 3.6, one displaying the averaged signal from a detector registering random stray photons, and the other showing an overlap of several of these detected pulses without averaging. The averaging is achieved by adding several of the pulses over time — therefore the height of the signals in this picture does not show the actual voltage amplitude but much rather how many of these signals appeared in the measurement duration. Instead, we expect the signal amplitude to be constant for all signals (as seen in Fig. 3.6(b)) which is why afterpulsing cannot be reduced by simply adjusting the trigger of the TimeTagger.

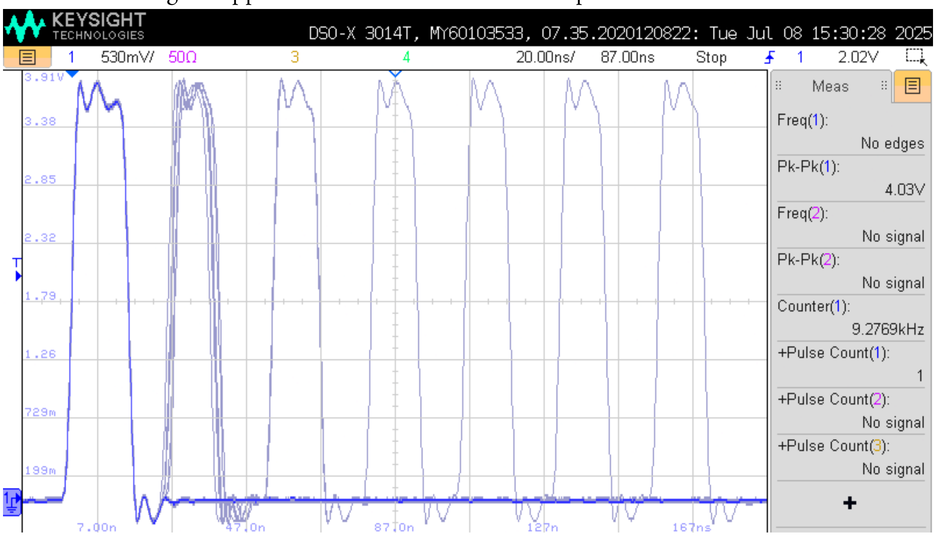
The equidistant pulses observable to the right of both pictures are most plausibly interpreted as afterpulses rather than genuine photon events. This conclusion is supported by two observations: (a) the spacing of the pulses coincides with the detector's dead time (approximately 22 ns; see Sec. A.1.2 of the appendix for a characterization of all detectors used in this thesis), and (b) reducing the incident light with an iris lowers the overall pulse count, yet the residual afterpulses remain regularly spaced, whereas signals from independent photons would be expected to appear at random intervals.

Given that the secondary dips in Fig. 3.3 exhibit the same 22 ns periodicity, it remains reasonable to attribute them to detector afterpulsing as well. Examination of the coincidence rate $R_{si}(\Delta t)$, shown in Fig. 3.5, suggests why this effect manifests in the data: when a true coincidence is detected, one or both detectors may produce afterpulses following the initial signal and their respective dead times, leading to secondary maxima around 22 ns.

Afterpulsing can be reduced by choosing a lower gain which, however, also leads to a lower detection efficiency. We can confirm this by looking at Fig. 3.7, as compared to Fig. 3.6 the integrated afterpulses decrease relative to the size main pulse when the gain is reduced. The influence of operating the detectors with lower gain on the $g^{(2)}$-function is visible in Fig. 3.8, confirming further



(a) Averaged signals, captured for a few seconds — the height of the signal corresponds to how common these signals appeared rather than their actual amplitude



(b) Recording of the overlapping signals

Figure 3.6: Oscilloscope traces of random stray light detected by the single-photon detector (*SPDMA*) operated at full gain. The main detection events appear on the left at the oscilloscope trigger, while afterpulsing is visible as periodic repetitions of these signals. **a)** Shows an averaging of signals over time while **b)** simply shows the overlapping traces of several signals recorded after one and another.

Figure 3.7: Oscilloscope trace of random stray light detected by the single-photon detector (*SPDMA*) operated at half gain. Signal integrated, therefore showing that the afterpulsing is reduced in comparison to Fig. 3.6

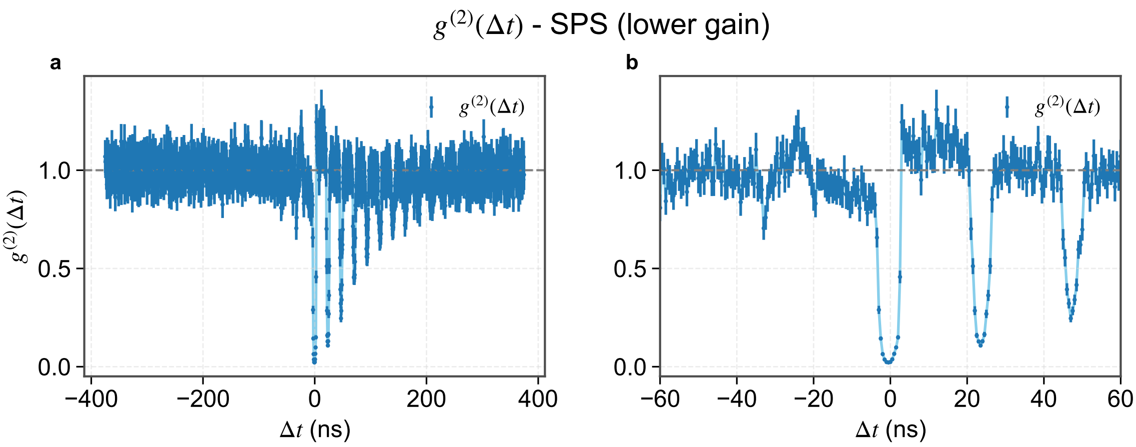


Figure 3.8: $g^{(2)}$-function of the SPS, calculated using Eq. 3.1, **a)** showing a larger time window from −400 ns to 400 ns, **b)** showing a smaller time window between −60 ns to 60 ns

that the secondary dips are indeed caused by the detector ringing and therefore appear to a lesser extent when a lower gain is used. This graph further confirms to us that the main dip at $\Delta t = 0$ is not object to these changes. The afterpulsing has therefore no influence on the overall result, that the SPS produces photons in the single-photon realm since for this, only the depth of the main dip and no secondary dips are relevant.

3.3 Michelson interferometer and Quantum Eraser

As explained in the previous section, a particle-like behavior of photons can be found by looking the anti-correlative features of the output of single photons on a beam-splitter. At the same time, photons also undeniably possess wave-like properties which can be demonstrated by their ability to interfere with one and another. An even more striking realization, however, lies in the fact that photons are able to interfere with themselves. This ability can be demonstrated by observing single photons in an interferometer. For this thesis, this effect was shown on a Michelson interferometer as pictured in Fig. 3.10.

To fully understand the effect of single photon interference, I will first briefly introduce the formalism to describe the effects observed with the Michelson interferometer and further by turning it into a Quantum Eraser using three polarizers as pictured in Fig. 3.13. I will then give the results of my measurements in two following parts (Sec. 3.3 and Sec. 3.3.3).

3.3.1 Single photon interference and which-path-information

In order to understand how interference of a photon with itself can occur, we have to return to its description within the formalism of quantum mechanics before and after its interaction with the beam splitter. So far, we have treated the beamsplitter-photon-interaction as basically classical, where the photon, understood as a particle, has to choose one path due to the fact that it is indivisible (hence, its particle nature). Experimentally, this is also exactly what we observe when simply looking at the beam splitter outputs, as we have seen in Sec. 3.1.

However, in quantum theory, a given state is believed to be altered by measurements such as the photon-detection used in the previous sections since within its formalism, the measurement process is presented by projecting the state onto the eigenstates of the observable of interest. To find out more about the true state of the photon and its characteristics in a different process of measurement, we shall therefore attempt to describe its state before measurement.

Looking at the schematic in Fig. 3.10, let us assume that a photon has already exited the first beam splitter through output d, meaning that is ready to enter the interferometer through the beam splitter input a'. We can denote its state at this point as

$$|\Psi_{\text{in}}\rangle = |1\rangle_{a'}\,|0\rangle_{b'} \tag{3.6}$$

since, in this idealized description, we can be sure that there is no second photon entering through input port b'. The photon in question can now either be reflected or transmitted on the beam splitter surface, both with a likelyhood of 50 %. If we were to measure the photon's position at this point, we would get one definite result; however, for as long as no further disturbance or measurement occurs, we note down the new state of the photon as being in a superposition of being reflected and then exiting the beam splitter at output d' and being transmitted and exiting the beam splitter at output c'. This state is therefore then

$$|\Psi_{\text{split}}\rangle = \frac{1}{\sqrt{2}}(|1\rangle_{c'}\,|0\rangle_{d'} + e^{i\phi}\,|0\rangle_{c'}\,|1\rangle_{d'}) \tag{3.7}$$

with $e^{i\phi}$ representing the phase shift caused by the reflection as well as possible path length differences in one of the interferometer arm.

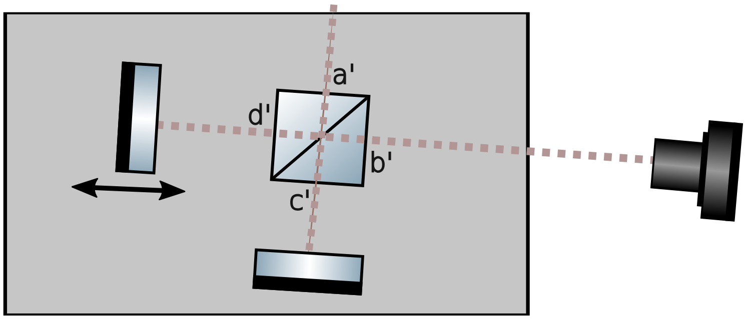


Figure 3.9: Schematic showing the position and names of the beamsplitter outputs in the interferometer (Fig. 3.10).

The mirrors on both outputs of the beam splitter reflect the photon in both arms of the interferometer back onto the beam splitter, meaning that $|\Psi_{\text{split}}\rangle$ is our new input state. The operation of the beam splitter remains the same, turning our state after recombination into

$$|\Psi_{\text{reco}}\rangle = \frac{1}{\sqrt{2}}\left(\frac{1}{\sqrt{2}}(|1\rangle_{\text{a'}}|0\rangle_{\text{b'}} + |0\rangle_{\text{a'}}|1\rangle_{\text{b'}}) + \frac{1}{\sqrt{2}}e^{i\phi}(|1\rangle_{\text{a'}}|0\rangle_{\text{b'}} - |0\rangle_{\text{a'}}|1\rangle_{\text{b'}})\right). \tag{3.8}$$

Reminding ourselves that the notation above is just a different representation of the photon's wavefunction, it becomes clear why after this second interaction with the beam splitter, interference can appear at output b' where the detector is placed. We can retrieve the probability for photon detection here by applying $\hat{P_{\text{b'}}} = \hat{I_{\text{a'}}} \otimes \langle 1|_{\text{b'}}|1\rangle_{\text{b'}}$, with the identity operator $\hat{I_{\text{a'}}}$ signalling that the states in output a' remain unchanged (as no measurement takes place here). Finally, when taking into account the introduced phase difference caused by the path length (the phase differences introduced by the reflection on the beam splitter do in the end cancel out as photons in each arm need to be reflected and transmitted once in order to arrive at b'), this leads us to the expression

$$P(1_{\text{b'}}) = \frac{1}{2}\cdot(1-\cos\phi) \tag{3.9}$$

with $P(1_{\text{b'}})$ denoting the probability to detect a photon in b' [11, 27]. Summing over many photons, this sinusoidal property of the probability becomes visible. While it remains true that for a single photon, measurement result remain classical in the sense that it can either be detected or not detected, it should be very clear that an interference pattern measured over several single-photon events only becomes understandable under the assumption that after the first interaction with the beam splitter, the photon is in fact in the superpositional state described by $|\Psi_{\text{split}}\rangle$.

Yet, this state can be altered by incorporating additional measurements inside the interferometer: If we, for example, would try to detect whether there is a photon within the interferometer arms, the photon could no longer remain in its superposition as the result of such a measurement must remain distinct and therefore is a projection onto the eigenvalue the measurement outcome. However, this detection would likely destroy the photon entirely (e.g. if we were to use a single-photon detector as for the other measurements in this thesis), meaning that it would no longer be available to test what happens to the interference pattern after dissolving the superposition in this way. Another

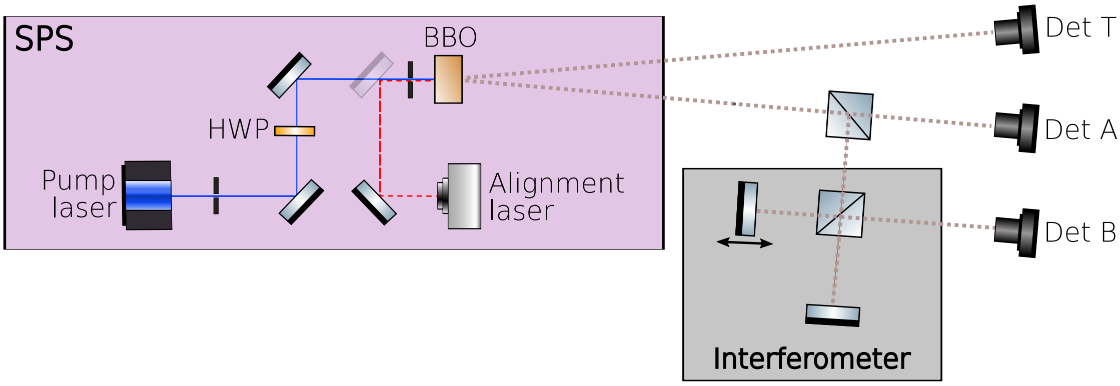


Figure 3.10: Schematic of the Michelson interferometer used to show single photon interference: The interferometer is inserted after a first 50:50 beamsplitter, ensuring that a measurement of the $g^{(2)}$-function of the single photons remains possible. The actual interferometer consists of a 50:50 beamsplitter as well as one fixed and one moveable mirror set on a translation stage with piezo drive (resolution: 0.6 nm) [22].

possibility is therefore to instead "tag" the photons, meaning that we could retrieve the information about which part they took by later measuring the tag they carry (the result of which would also have to be distinct, thereby unavoidably destroying the superposition).

One way to realize such "tagging" is to introduce two orthogonally set polarizers into the interferometer arms, as pictured in Fig. 3.13. A further the discussion of the experimental outcome of this setup known as a Quantum Eraser will be discussed in Sec. 3.3.3

3.3.2 Michelson interferometer

In the setup pictured in Fig. 3.10, the movable mirror (as indicated by the double-sided arrow) is clamped to a translation stage that can be displaced with an accuracy of 0.6 nm using a piezo crystal. This piezo (directly driven by a piezo controller) can be controlled by the kit software and via python. Therefore, measurements with the interferometer were taken using the kit software and using python code that directly worked with the raw data recorded by the TimeTagger here as well.

Additionally, the light employed in the interferometer passes a first beam splitter before entering, making it possible to measure the $g^{(2)}$-function of the light used. This is of special interest to us, as this way, it can be confirmed that we still work in the single-photon regime when installing the interferometer.

The interferometer was set up using the alignment laser as well as an LED included in the kit that can be used for fine adjustments due to its shorter coherence lengths. Generally, the instructions given by [11] for the setup-process were followed.

The measurement results of performing the experiment with the kit software, together with a measurement of the $g^{(2)}(0)$-value measured at the different piezo positions can be found in Fig. 3.11. The value of interest is here the double coincidence rate R_{TB} since we are still interested in detecting the heralded photons in a single photon state. For reference, the overall count rate of Detector B was, however, also included in this graph.

Furthermore, in Fig 3.11b, the $g^{(2)}(0)$-values at the different piezo positions are pictured. As we can clearly see, the values all remain below the classical limit of $g^{(2)}(0) = 1$. Yet, there seems to be

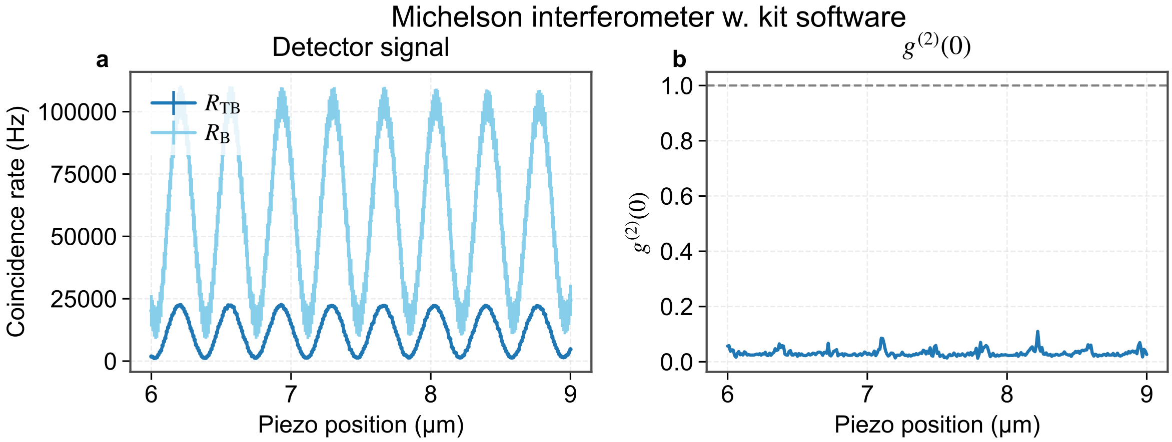


Figure 3.11: Results of measurements with the Michelson interferometer as pictured in Fig. 3.10, recorded using the kit software: **a)** shows the count rates R_B and R_{BT} at different positions of the piezo crystal moving the translation stage with one of the mirrors; **b)** showing the value of $g^{(2)}(0)$ of detector signal A and B at these positions to confirm that the photons measured remain in the single-photon realm.

some structure visible: The value of $g^{(2)}(0)$ seems to notably peak whenever the signal measured by Detector B or the double coincidence rate is at a minimum. As it is mentioned by Thorlabs [11] as well, this effect likely is based in the fact that the $g^{(2)}$-function is heavily dependent on double as well as triple coincidence rates including the signal of Detector B. For positions of negative interference, this signal gets so low that the corresponding coincidence rates are no longer representative, leading to unexpected peaks of the $g^{(2)}(0)$-function.

Furthermore, the same effect was measured using self-written python code to control the piezo and record the data. The results of this measurement can be found in Fig. 3.12. To confirm that what we are observing here is in line with the predictions made in Sec. 3.3.1, equation 3.9 was fitted to this data. Visually, this fit seems to describe the recorded data very well. However, the slightly raised reduced X^2-value suggests that the errors on the measurement data were underestimated. This is likely due to the fact that only the error stemming from false coincidences as suggested by Eq. 3.2 were considered while errors e.g. stemming from the piezo movement (albeit that if this error should indeed be negligible, if it is really on the scale of the resolution of 0.6 nm as stated by the manufacturer) were ignored. It is also likely that the dark count rates play into the error here to a larger extent since the count rates for positions in which destructive interference occurs become rather low.

The sinusoidal form of the measurements can therefore confirm to us that we seem to generally be dealing with an interference phenomenon. All the same, it should be mentioned that the appearance of this pattern does not yet confirm to us that it is fact self-interference that we are observing. It could very well be that enough photons enter at interferometer at the same time for them to be able to interfere with each other and therefore not providing strong evidence that it is in fact the superposition of the photon in both interferometer arms that leads the rise of an interference pattern. It therefore seems necessary to confirm that the light source used is dim enough (meaning that the average number of photons produced within a certain time frame is low enough to be sure that it is likely that photon interacting with itself).

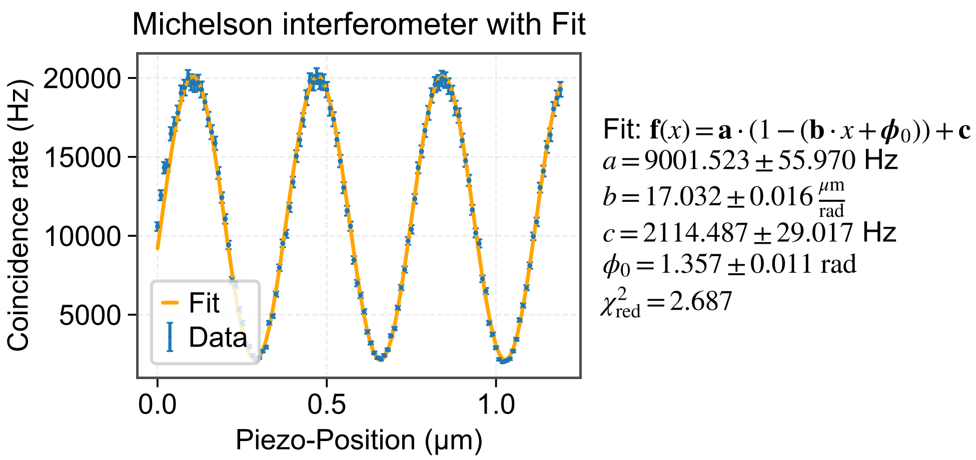


Figure 3.12: Measurement results of the Michelson interferometer, displaying the coincidence rate R_{TB} and a fit of the function suggested by Eq 3.9. The fit seems to describe the data visually well, suggesting that the pattern observable is in line with the predictions made for single-photon interference.

For this, we should consider the coherence length of the photons used: According to Thorlabs [11, 124], one photon has a coherence length of $l_c = \frac{\lambda^2}{=}65.6\,\mu m$[5]. The maximal difference in path length can not supersede l_c; we can therefore use it to calculate the maximal time frame in which it would be possible for a second photon 2 to enter the interferometer in order for it to still be able to interfere with photon 1 (assuming that photon 1 is in the longer arm of the interferometer). From this, we get a maximal time difference of

$$\Delta t_{\text{interferometer}} = l_c / c_{\text{air}} = 0.2189\,\text{ps} \tag{3.10}$$

with $c_{\text{air}} = 2.99712 \times 10^8\,\text{m}\,\text{s}^{-1}$ denoting the speed of light in air, calculated using the refractive index of air $n_{\text{air}} = 1.00027$ under regular conditions for light with $\lambda = 810\,\text{nm}$ [23].

As the production of photons of the source used is uncorrelated (we can conclude this from the unheralded $g^{(2)}$-function, as pictured in Fig. 3.2b), we can assume that the average time difference between to photons arriving at the interferometer is simply given by

$$\Delta t_{\text{source}} = \frac{1}{R_{\text{interferometer}}} \tag{3.11}$$

with $R_{\text{interferometer}}$ being the rate of photons at the interferometer entrance per second (meaning after the first beam splitter used for the GRA-experiment). Since we have no means of measuring this rate directly, we can estimate it using the count rates of Detector A as we would expect it to be the same for both beam splitter-outputs of beam splitter 1. Furthermore, we should pay attention to the limited detector efficiency: We know that the detectors (operated at full gain) used have an

[5] Theoretically, it would be possible to measure this coherence length using the interferometer by observing the overall range in which interference occurs. Due to the time limitation and interdisciplinary nature of this work, this measurement could not be performed and we will therefore work with the theoretical value $l_c = \frac{\lambda^2}{\Delta\lambda} = \frac{810^2}{10}\text{nm} = 65.6\,\mu\text{m}$ as provided by the manual.

efficiency of about $\epsilon_{\mathrm{Det}} = 43\,\%$ at 820 nm and since we do not want to underestimate the actual rates of photons produced, we will simply use this value even though the detection efficiency might be slightly higher for the photons in the cone of the SPS which have an average wavelength of 810 nm. Therefore, we arrive at a value of

$$R_{\mathrm{interferometer}} = R_{\mathrm{A}}/\epsilon_{\mathrm{Det}} = 720.93\,\mathrm{kHz} \tag{3.12}$$

with $R_{\mathrm{A}} \approx 310\,\mathrm{kHz}$, measured before the measurement displayed in Fig. 3.11. This finally results in a time difference of

$$\Delta t_{\mathrm{source}} \approx 1.39\,\mu\mathrm{s} \tag{3.13}$$

As we can see from this, the average time difference between the photons produced is already much higher than the coherence length of a single photon.[6] Additionally, we should note that not all of the photons detected by either Detector A or Detector B are the single photons in which we are interested (and which we actually use for the display of our interference pattern in the form of the coincidence rate R_{TB}). Therefore, the time interval in which single photons enter the beam splitter can be expected to be even larger.

While, due to the fact that all these processes are statistical, it can nonetheless happen that two photons enter the interferometer shortly after another and interfere, this can only be a very small percentage of the overall events detected. We can in fact even calculate this percentage by assuming that the overall distribution of time difference is Poissionian (once again based on the findings of Fig. 3.2). We therefore expect the probability to detect k photons within a time interval of Δt to be given by

$$P(k|\Delta t) = \frac{(R\Delta t)^k \cdot e^{R\Delta t}}{k!} \tag{3.14}$$

with R being the average rate of events. For a time interval equivalent to the coherence length of the photons, we therefore get a probability of $P(2|t_c) = 2.068 \cdot 10^{-10}$ to detect two photons, therefore confirming the statement made above that such bi-photon interference events remain extremely unlikely.

From the distance of the maxima in the interference pattern, we can in theory determine the wavelength of the detected photons. The results of this calculation can be found in the appendix in Sec. A.2. However, the calculated wavelengths from these interference patterns do not correspond to our expected wavelength of about 810 nm. This suggests that the scaling of the x-axis, meaning the distance travelled by the piezo translation stage is somehow wrong. Sadly, this mistake was found to late in the writing process to still be fixed. The stated distances within this section should therefore be taken with a grain of salt.

We can thus conclude that the interference pattern observed is indeed due to "the photon interfering with itself". In a classical picture, this would confirm to us that the photon does indeed behave like a wave which together with the above established finding that the $g^{(2)}$-function still suggest particle-properties seems to imply a contradiction in what the nature of the photon really is. We should, however, once again pay attention to the fact that particles as well as waves are concept that were introduces without objects such as photons being even known to exist at all.[7] Attributing a

[6] I have chosen to not include an error calculation for these values since this is just a rough estimation anyway. The values are different enough in order to assume that an error on e.g. the count rates will not have a large influence on this fact.

[7] Notably, this is explicitly mentioned in the original GRA-paper, in which they write"Indeed, if we want to use classical

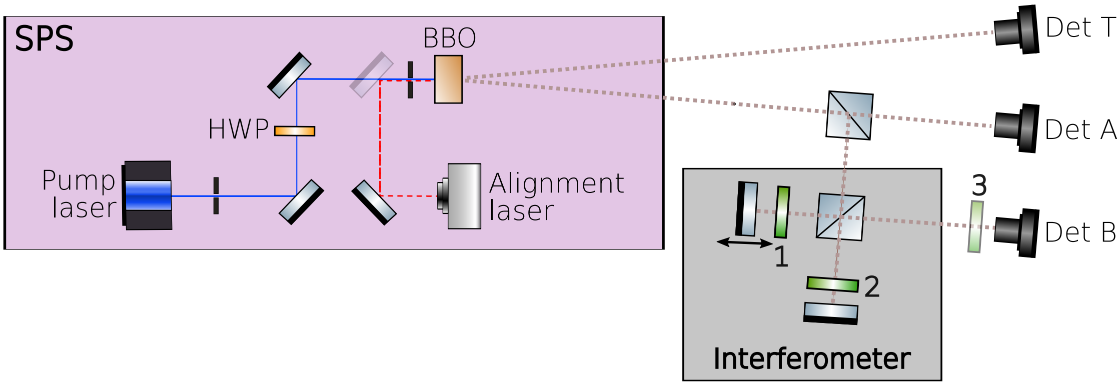


Figure 3.13: Schematic of the Quantum Eraser, based on the interferometer in Fig. 3.10: Three additional polarizers were inserted, with 1 and 2 oriented orthogonally (0° and 90°), and polarizers 3 being added optionally with a set angle of 45° to erase the effect of polarizer 1 and 2

dualistic nature as the word "wave-particle-dualism" seems to imply should therefore be treated with a certain caution as the photon is in fact not a magical object that somehow holds to ways of being in one but instead presents to us as a supposedly real entity which simply behaves differently in different environments. Further, the above described experiment teaches us that the photon must have the ability to exist in superpositional states. The experiment to follow will explore this concept further and moreover show that measurement leads to a destruction of such superpositions as well as to a breach in the supposedly dualistic appearance of the photon.

3.3.3 Quantum Eraser

As already described, the interferometer can be built into a so-called quantum eraser by inserting first two and then three polarizers with different orientations. In a first measurement, two polarizers (1 and 2 in Fig. 3.13) with the same orientation were inserted into the two interferometer arms to confirm that their insertion does not influence the general measurement results apart from slightly reducing the overall count rates. Then, one of the polarizers was turned to be orthogonal to the other one, leading to an almost complete disappearance of the interference pattern as we can see in Fig. 3.14. Instead, that the count rates now remain stable for all positions of the movable mirror. Finally, a third polarizer was added at the output of the interferometer, set to a position between the orientation of the first two polarizers. Unanticipatedly, this leads to a recovery of the interference pattern, albeit with an even smaller amplitude as before.

These effects can be understood by recognizing that a measurement represents a disruption of the state evolution of a quantum system in superposition. Measurement outcomes appear classical in that they yield definite, discrete results. Consequently, the measurement apparatus must interact with the photon's state in a way that eliminates apparently contradictory properties. In our setup,

concepts, or pictures, to interpret these experiments, we must use a particle picture for the first one («the photons are not split on a beam splitter »), since we violate an inequality holding for any classical wave model. On the contrary, we are compelled to use a wave picture («the electromagnetic field is coherently split on a beam splitter ») to interpret the second (interference) experiment. Of course, the two complementary descriptions correspond to mutually exclusive experimental set-ups." [17, 178f].

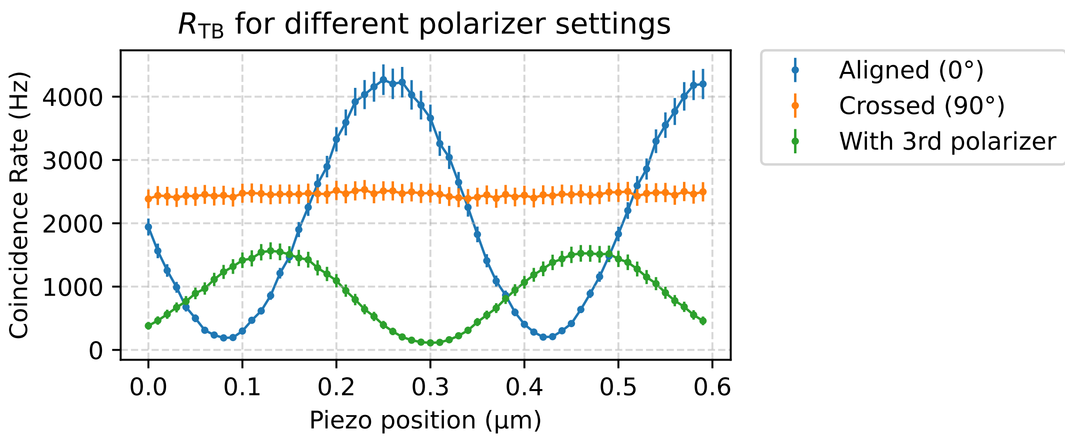


Figure 3.14: Figure showing the coincidence rate R_{TB} for different piezo positions and three different polarizer settings. Overall, we can see that for crossed polarizers the interference pattern disappears but is restored when a third polarizer set to 45° is inserted.

the polarizers placed in the two interferometer arms are perpendicular to each other. A photon that passes through one polarizer cannot pass through the other. By measuring its polarization, we can determine which path the photon took. This knowledge is incompatible with the photon being in a superposition of both paths simultaneously, and as a result, the interference pattern vanishes.

An even more precise explanation can be given when returning to the formalism describing this experimental setup: By inserting the polarizers, the state given in Eq. 3.7, turns into

$$|\Psi_{\mathrm{split}}\rangle = \frac{1}{\sqrt{2}}(|1_{c'}, 0_{d'}\rangle |V\rangle + e^{i\phi} |0_{c'}, 1_{d'}\rangle |H\rangle) \tag{3.15}$$

with $|V\rangle$ and $|H\rangle$ respectively representing a vertical and horizontal polarization determined by the polarizer settings.

The state after recombination (Eq. 3.8) can similarly be extended by adding the polarization base:

$$|\Psi_{\mathrm{reco}}\rangle = \frac{1}{\sqrt{2}}(\frac{1}{\sqrt{2}}(|1_{\mathrm{a'}}, 0_{\mathrm{b'}}\rangle |V\rangle - |0_{\mathrm{a'}}, 1_{\mathrm{b'}}\rangle |V\rangle) + \frac{1}{\sqrt{2}}e^{i\phi}(|1_{\mathrm{a'}}0_{\mathrm{b'}}\rangle |H\rangle + |0_{\mathrm{a'}}1_{\mathrm{b'}}\rangle |H\rangle)). \tag{3.16}$$

The disappearance of the interference term is now finally caused by the fact that the measurement operator has to be extended into the polarizer base as well. We therefore now apply $\hat{P_{\mathrm{b'}}} = \hat{I_{\mathrm{a'}}} \otimes \langle 1|_{\mathrm{b'}} |1\rangle_{\mathrm{b'}} \otimes \hat{I_p}$. This new base leads to the fact that mixed path terms are no longer compatible due to their different polarization. Finally, this means that the new outcome of measuring a photon at the detector is simply

$$P(1_{\mathrm{b'}}) = \frac{1}{4}, \tag{3.17}$$

meaning that any term dependent on the path length and the thereby induced difference in phase has completely disappeared. For a more detailed discussion of this calculation, see Thorlabs [11, 30].

In the case of the real experiment, this form of "tagging" is not always perfect since the 90°

difference in orientation is hard to achieve as the polarization orientation and calibration is done by hand. Therefore, we can still see some slight interference structures when looking at Fig. 3.15.

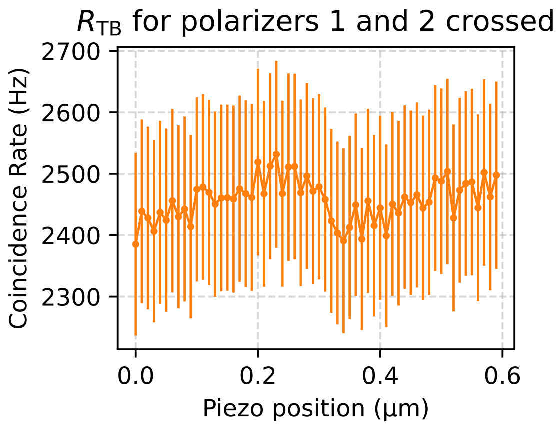


Figure 3.15: Closeup of the coincidence rate R_{TB} in the case of crossed polarizers 1 and 2 showing that a slight interference-like structure seems to be preserved. Data taken from the same measurement as Fig. 3.14.

When the third polarizer gets inserted, the interference pattern reappears. This is due to the fact that this polarizers "deletes" the information about which path the photon took (consequently the name "quantum eraser"). Therefore, the superposition gets restored and the interference pattern reappears. The shift of the maxima by half a period can be explained by the piezo not being perfectly reset after each run. Further, the reduced amplitude is to be expected as a feature of the amount of photons being reduced with each new polarizer added (and therefore more terms of the overall wavefunction disappearing in the case of measurement).

According to Thorlabs [11, 31], the new probability of detecting a photon with all three polarizers inserted is now

$$P(1_{b'}) = \frac{1}{8}(1 - \cos\phi). \tag{3.18}$$

This reduction of the maximal amplitude to a quarter in comparison to Eq. 3.9 seems in line with the measurement data.

While there are many ways of understanding what the quantum eraser is supposed to tell us about the quantum world, I want to refrain from going into further specifics about the interpretations of this phenomenon here. However, two findings should be nonetheless be noted here: For once, an interesting observation lies in the fact that the "Which-way"-information created by the polarizers does not have to be read out in order for it to influence the interference pattern. One way of understanding this effect is by saying that this speaks to complementarity as a principle in quantum mechanics that can be related back to the uncertainty principle. However, this might be confusing as seemingly, no measurement regarding the polarization takes place. Another way of speaking about this phenomenon therefore proposes to instead relate the disappearance of the interference pattern to a loss of coherence related to the distinguishability of the particle that the polarizers introduce. [8]

[8] This seems to be an interpretation very close to the formalism, we should, however, also note that even this way of speaking of the quantum eraser introduces quantum-specific concepts such as indistinguishability to this discussion. It is therefore not a strict reiteration of the formalism just by itself.

Another interesting aspect is the potential "delay choice" that can be implemented in this experiment. This idea goes back to discussions concerning the role of the observer in quantum measurements who in a collapse-based interpretation said to be able to freely choose whether to detect the wave or particle nature in this experiment long after the original interaction with the measurement apparatus. This is also the interpretation of the experiment proposed in the original paper in which the setup of the quantum eraser was developed [24]. Another way of looking at this delayed choice is by rather treating the "choice" between the particle and wave nature of the photon as a post-selection of measurement data (for this, see e.g. Ellerman [25]), similarly to the argument presented in Sec. 2.2 about the role of heralding in the SPS.

3.4 Bell tests

The last series of experiments described in this thesis are a simplified version of Bell tests. For this, additionally to the original kit, the extension kit EDU-QOPA1/M by Thorlabs was used, providing a Pair-BBO that can produce polarization entangled photons. The specifics of this creation process were given in Sec. 2.2.

In this section, I will shortly explain the goal of a Bell test and introduce the Bell equation used for this thesis called the CHSH-inequality. Further, I will give a short evaluation of the potential limitations on the results of Bell tests. In the second part, I will then present the setup used to perform Bell tests for this thesis, discuss the results and explain the influence of spatial and temporal walk-off.

3.4.1 Quantum locality and entanglement

As we have learned in the previous section, quantum object seem to have the ability to exist in certain states that are unknown to us from classical objects, such as the ones observable in our everyday environment. One of these previously unknown properties is the ability to exist in a superposition. Throughout the development of quantum mechanics, another surprising and controversial prediction was the creation of entangled objects.[9] Entanglement describes two entities (such as two photons) created in a shared superposition that is such that the state of object A must become distinct when the state of object B is measured. In other words, the superposition of both objects must end "together", no matter how far apart they are.

This form of behavior warrants a strong correlation between the states of object A and object B that can be tested. Bell showed in 1964 that, assuming the existence of so-called hidden local variables λ, it could be proven that the expectation value of measurements of the spin in the direction of $\vec{a}$ and $\vec{b}$ in the EPR-paradoxon was equal to

$$P(\vec{a},\vec{b}) = \int \mathrm{d}\lambda\, \rho(\lambda) A(\vec{a},\lambda) B(\vec{b},\lambda) \tag{3.19}$$

with A and B being the measurement results of the spin measurements. Further, Bell demonstrated that this expectation value was incompatible with the expectation value suggested by quantum theory in the case of two entangled objects [27, 14–21]. This incompatibility can be stated in the form of an inequality using a combination of different measurement parameters (e.g. represent

[9] For an overview on the history of its introduction to the scientific discourse, see for example Fine [26].

by different directions of spin measurements such as $\vec{a}$ and $\vec{b}$). Namely, the existence of hidden local variables would suggest that the measurements of these different parameters in a number of combinations would remain below a certain level of correlation, as their measurement outcome is not determined by the measurement performed on the other particle but instead solely by some local hidden information-carrier or environment factor λ (represented in the above mentioned Eq. 3.19 by the fact that the probability distribution ρ characterizing the state of the two particles does not depend on $\vec{a}$ and $\vec{b}$). We can note this down as follows

$$|P(a,b) - P(b,c)| \leq 2 - P(b',b) - P(b',c) \tag{3.20}$$

with P describing the correlation function, equivalent to the formulation of the expectation value in Eq. 3.19 and the parameters a, b, ...now denoting parameters on the measurement apparatus that could e.g. be equal to certain polarizer settings [28]. The position of the parameters in $P(a,b)$ indicates to which subsystem or particle each measurement setting belongs.

A difficulty of this formulation remains in the fact that we cannot test correlations directly but instead work with imperfect measurement devices and count rates. We therefore need a reformulation of this formula, similarly to the reformulation of the g_2-function as discussed in Sec. 3.1. In this thesis, we will use the CHSH-inequality as a reformulation which is suitable for a setup as the one suggested in Fig. 3.16 in which polarization entangled photons are used. For this, the correlation functions can be rewritten in terms of the probabilities $\omega(A(a)_\pm, B(b)_\pm)$, signaling the probability that either a photon emerges from a polarizer set to a certain setting a ($A(a) = +1$ etc.) or the probability that it is not transmitted ($A(a) = -1$ etc.) [28]. Following Clauser et al. [28], we arrive at the expression

$$P_\lambda(a,b) = \omega(1,1|\lambda) - \omega(-1,1|\lambda) - \omega(1,-1|\lambda) + \omega(-1,-1|\lambda) \tag{3.21}$$

with the overall inequality then presenting as

$$P(a,b) - E(a,b') + E(a',b) + E(a',b') = S \leq 2 \tag{3.22}$$

as we can conclude from Eq. 3.20.

Since we cannot measure the opposite of a photon being transmitted directly, we depend on orthogonal polarizer settings. This allows us to rewrite Eq. 3.21 in terms of polarizer settings as

$$P(\alpha,\beta) = |\langle\Phi|\alpha,\beta\rangle_{1,2}|^2 - |\langle\Phi|\alpha,\beta+\tfrac{\pi}{2}\rangle_{1,2}|^2 - |\langle\Phi|\alpha+\tfrac{\pi}{2},\beta\rangle_{1,2}|^2 + |\langle\Phi|\alpha+\tfrac{\pi}{2},\beta+\tfrac{\pi}{2}\rangle_{1,2}|^2 \tag{3.23}$$

with $|\langle\Phi|\alpha,\beta\rangle_{1,2}|^2$ denoting the probability that a measurement on the original state $|\Phi\rangle$ results in transmission of photon 1 and 2 through polarizers with the orientation α and β, denoted by the the polarization eigenstates $|\alpha\rangle_1 |\beta\rangle_2 = |\alpha,\beta\rangle_{1,2}$ [29, 68].

Finally, we can assume these probabilities to be proportional to the normalized count rates, meaning e.g. that

$$|\langle\Phi|\alpha,\beta\rangle_{1,2}|^2 \propto \frac{R_{a_0,b_0}(\alpha,\beta)}{R_{a_0,b_0}(\alpha,\beta) + R_{a_e,b_0}(\alpha,\beta) + R_{a_0,b_e}(\alpha,\beta) + R_{a_e,b_e}(\alpha,\beta)} \tag{3.24}$$

with the indices of the different count rates denoting either the ordinary angles α and β belonging to the set (a,b) or the extraordinary angles $\alpha + \frac{\pi}{2}$ and $\beta + \frac{\pi}{2}$ used as a substitute for the non-transmission of photons (as suggested by Thorlabs [29, 70])

The proportionality is here defined by the detector efficiency. As we can assume this to be the same for all detectors used, we finally arrive at the expression

$$P(a,b) = \frac{R_{a_0b_0}(\alpha,\beta) - R_{a_0b_e}(\alpha,\beta) - R_{a_eb_0}(\alpha,\beta) + R_{a_eb_e}(\alpha,\beta)}{R_{a_0b_0}(\alpha,\beta) + R_{a_0b_e}(\alpha,\beta) + R_{a_eb_0}(\alpha,\beta) + R_{a_eb_e}(\alpha,\beta)} \tag{3.25}$$

for the overall correlation function P [29, 70].

For the different angles chosen as a, b, b' and a', we therefore arrive at a set of angle combinations that can be used to measure S for the setup in Fig. 3.16. These sets are listed in Tab. 3.1

Set	a_0, b_0 (°)	a_0, b_e (°)	a_e, b_0 (°)	a_e, b_e (°)
1 (a, b)	0, 22.5	0, 112.5	90, 22.5	90, 112.5
2 (a, b’)	0, 67.5	0, 157.5	90, 67.5	90, 157.5
3 (a’, b)	45, 22.5	45, 112.5	135, 22.5	135, 112.5
4 (a’, b’)	45, 67.5	45, 157.5	135, 67.5	135, 157.5

Table 3.1: Measurement settings with corresponding angles in degrees for a and b.

In conclusion, if now, using a combination of measurements with different polarization settings as listed in Tab. 3.1, we measure an S-value that is higher than the limit of two given by Eq. 3.22, this suggests to us that we are measuring a correlation between the measurement outcome on photon 1 and 2 that cannot be explained by both photons being locally influenced by some sort of hidden-variables that determines their state definitively. This strongly suggests that locality must operate differently for quantum objects: When two photons are created in an entangled state, a measurement on one can instantaneously influence the state of the other, regardless of the distance between them which is unlike the belief of classical physics in which changes in the states in enacted by entities in the local environment of an object.

Our version of this experimental setup still features some loopholes. One example for this is the fact that the distance between the two measurement sights is not large enough to be sure that no information between the devices could be exchanged, thereby explaining the correlation in a way in which classical locality is preserved [30, 9f]. Further, the limited detector efficiency could pose a problem after all since one could argue that due to the limitations of the data produced by it, the behaviour of the ensemble is after all not well described by these results [30, 13f]. The third common objection to Bell tests such as the one performed in this thesis is called the “freedom-of-choice loophole”. This describes the objection, that the choice of measurement settings (such as the polarizer angles) is not fully random and could therefore be the common cause leading to correlations in the measurement data. In the case of our measurements, little can be said in opposition to this criticism as the angles are predetermined and follow a clear pattern. However, other Bell tests e.g. using measurement parameters randomly chosen by volunteers have been performed that try to close this loophole [31].

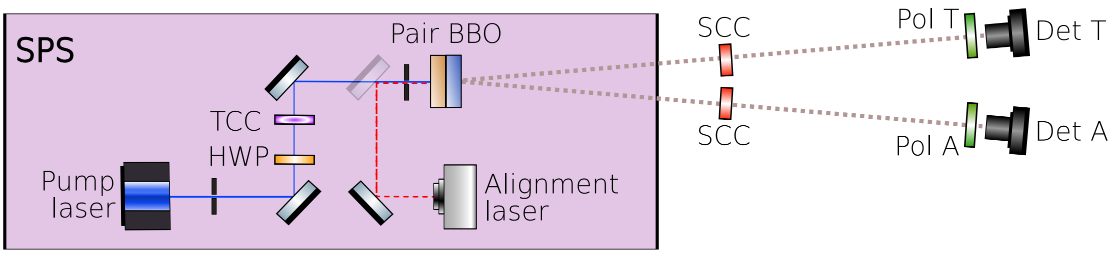


Figure 3.16: Schematic of the setup used to perform a Bell test. The Pair-BBO creates polarization entangled photons. Further non-linear crystals are used for temporal compensation (Temporal Compensation Crystal — TCC) and spatial compensation (SCC). The laser was powered at about 20 mW. The HWP is set to 22.5° to ensure that creation in both crystals of the Pair-BBO turns out to be equally likely.

3.4.2 Performing a Bell test (with loopholes)

The setup used for the Bell test performed for this thesis is, as already mentioned, pictured in Fig. 3.16. As it can be seen, additionally to the Pair-BBO that produces the entangled photons, further crystals are inserted to compensate for the spatial and temporal walk-offs between the different polarization states as given by Eq. 2.8.

Without going into further detail, the need for these crystals can be summarized as follows: Due to the different creation locations of photons in either Crystal 1 or Crystal 2 of the Pair-BBO, a phase difference would in theory arise between VV and HH pairs, reinforced by the different refractive indices due to the different polarization in crystal 2. This effect is even larger when the detection angle is sufficiently big and therefore even more pairs with larger differences in path lengths could be collected. The detection angle can be limited by closing the iris apertures on the detectors (as we will later also see in the measurement data). However, the phase difference can also be compensated by inserting another birefringent crystal, reversing the effect of the birefringence in the original Pair-BBO. For details on this effect see Thorlabs [29, 74ff].

This effect is further complicated by the fact that the photons created in the Pair-BBO are not monochromatic but instead can cover a range of different wavelengths are described by Eq. 2.4. The dispersion of the crystals in the Pair-BBO therefore lead to further differences in phase for pairs of different wavelengths. This can in approximation be reduced by matching the travel time that pairs of both polarizations need to travel through the pair-BBO (for an explanation of why this is an adequate mean of reducing this effect, see Thorlabs [29, 78ff]). This matching of travel times is achieved through yet another birefringent crystal that is, however, not inserted into the path of the photons but instead before the BBO-crystal into the pump beam. This crystal causes a delay shift between the horizontal and vertical polarization component of the pump beam that can be matched to the delay created by the Pair-BBO, therefore compensating for this "temporal" walk-off [29, 80]. The effect of this crystal can be seen in the measurement included in the appendix as Fig. A.5. The optimal setting of the temporal compensation crystal was chosen by setting Polarizer T to 45° and Polarizer A to −45° and then minimizing the coincidence rate between the two detectors by rotating the TCC, as suggested by Thorlabs [29, 39f]. The goal of this form of alignment is to cancel out the mixed-polarization terms that arrive through this change of the basis from $|H\rangle$ and $|V\rangle$ to $|D\rangle$ and $|A\rangle$, since in this case $e^{i\phi} = 1$.

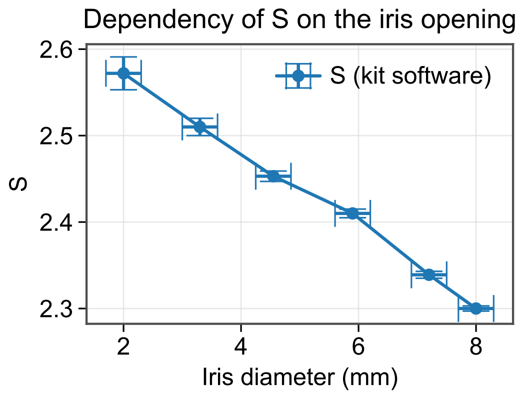


Figure 3.17: Dependency of the S-value in the detector iris aperture, S calculated by the kit software. The large errors in the iris diameter measurements are due to the difficulty of obtaining precise values, as the iris was already fixed to the detectors installed in the experiment. Therefore, a hand-held caliper was used.

Several Bell tests were performed with the setup as described above, including some using the kit software. For this part of the thesis, no difference could be observed between the results calculated using the kit software and those obtained by hand according to Eq. 3.21 together with the definition in Eq. 3.25. The errors on the S-values calculated by hand were estimated using error propagation together with an assumed error on the coincidence rates according to Eq. 3.2. The errors on the S-values determined using the kit software were calculated by the software automatically.

For each Bell test, 16 measurements of the coincidence rate between Detector T and Detector A were taken. The settings of the polarizers were varied according to Tab. 3.1. The average coincidence rates for the individual angle settings are included in the appendix in Sec. A.3.

With fully opened iris apertures on the detector optics, a value of $S = 2.29$ could be achieved (for the individual measurement data, see Tab. A.4). Higher values of S could be reached by further closing the irises due to the afore mentioned spatial walk-off for big apertures. An overview of this effect can be found in Fig. 3.17. Looking at the error bars in this plot, we can also see the downside of smaller iris apertures: Since the count rates are strongly reduced (see the tables in Sec. A.3), the statistical error on these measurements increase and longer measurement durations would become necessary.

The highest S-value of $S = 2.572 \pm 0.019$ could be achieved for an iris diameter of 2 mm. This value very clearly violates the CHSH-inequality as given in Eq. 3.21; it is even sufficiently close to the Tsirelson upper-bound of $S = 2\sqrt{2}$ for quantum observables. It can therefore be seen as an indicator for the quantum mechanical violation of a classical notion of locality, taking into account the reservations explained in the previous sections. [10]

[10] In some of the writing on Bell tests, it is suggested that the these tests exceeding an S-value of 2 disprove what is called "local realism". In the following section, we shall briefly see why the issue of realism is brought into this discussion in the first place.

3.5 Interim conclusion and outlook

We can summarize the results of this first part in the following way: We have seen that light in a single-photon state behaves in ways that is unknown to us from classical optics: When interacting with a beam splitter, this type of light does no longer "split" in two equal parts, as we would expect it from a wave; instead, a signal can only be measured on one of the outputs at a time. In classical physics, we would associate this type of behavior with a particle that is, by definition, indivisible.

However, we have also seen that light of this type (or these "single photons", as we sometimes call them when imagining light as made up of particles) has the ability to interfere. An especially striking form of this interference is its interference "with itself" which we can speak of when there is so little light present that what we observe must be the interference of a single, seemingly indivisible bundle of energy. The observation of this interference leads us to the concept of a superposition which is a feature that is specific to quantum objects or quantum entities.

The superposition of photons is usually destroyed in the measurement process. Photons can furthermore lose their ability to interfere if we introduce which-path-information. We have seen this effect in the "Quantum Eraser"-setup and have further shown that this information can be erased which leads to a reappearance of the interference pattern.

These experiments, in which we can imagine the photon to take "both possible arms" of the interferometer at the same time, can already suggest that quantum objects possess a specific type of locality that is different from the way locality is understood in classical mechanics. We have further investigated the particularities of quantum locality by performing a simple Bell test. Although this is not a definite proof due to the loopholes present, we have seen that the result of these Bell tests points towards another quantum peculiarity, namely entanglement.

Overall, the experiments performed in this thesis therefore provide a good introduction of the characteristics of the world that quantum mechanics seems to describe. Experimenting with single photons was therefore also enlightening to me personally, as it illustrated many of the abstract concept that I had earlier only studied theoretically. In this sense, I believe the Thorlabs kit to be a useful tool for students like me. Additionally, I was successful in performing all of the experiments without the use of the kit software. I would recommend this approach to future users since, in my opinion, the software documentation is rather sparse.

At the same time, many of the experiments performed could, of course, be explored in greater depth. While the overall measurement results were within the scope of what was to be expected, certain components — such as the piezo translation stage — would have warranted a more detailed investigation, similar to what I carried out for the single-photon detectors. Moreover, there are additional quantum properties and influential experiments that could be added in order to make the list of what makes the quantum world unique more complete. One example is the Hong–Ou–Mandel experiment, which probes the indistinguishability of quantum particles.

The results so far can nonetheless provide a good basis to ask further questions about quantum mechanics and the quantum viewpoint. In this part, I attempted to remain very careful and neutral in the language that I used to describe the phenomena at hand. In the next part of this thesis, we shall see the reason for this and discuss difficulties that arise from the attempt to interpret such phenomena further. We shall therefore close this chapter of being physicists for now, and move on to becoming philosophers.

Part II

Part II

CHAPTER 4

Approaching the real

4.1 Physics, philosophy and questions about reality

Most of the experiments performed for this thesis were not just formative for the development and establishment of quantum mechanics as a viable and successful physical theory. Many of their results have historically also been a cause for discussion, often centered around concepts arising from the dichotomy of the successful formal prediction of experimental results and the attempt to make sense of these results using the terms of "old physics", such as "particles" and "waves".

The need to develop concepts or, maybe in other words, the need for interpretation of the mathematical formalism is not intuitively evident to some physicists, especially considering that the predictions of the formalism do fit the experimental data extremely well –– a fact which is once more proven by the results of this thesis but is even more so reflected in the work of thousands of others skilled experimentalists working with setups that by far extend the level of complexity reached in this work. Philosophers of physics like to respond to this by saying that the formalism of quantum mechanics does not yet provide a definitive answer to ontological questions and that this connection to ontology cannot be provided by physics on its own. Ontology, depending on who practices it, describes the study of the true being of entities such as photons, elephants or humans and asks about the qualifications and structure of being per se. In my experience, physicists care rather little about the structure of being per se; they do, however, care at least to some extent about the relationship between the phenomena observed by them and reality.[1]

[1] Throughout my time in the Hoffertberth group, I have tried to ask some of my colleagues about their understanding of the relevance of their work for an understanding of reality or as a quest for truth. The answers to my questions were diverse, however, most of them contained intuitions that can be summarized under the following two statements: I. The relationship of the work of these experimental physicists and broader questions about the workings of the world is not as straightforward as one might be led to believe since oftentimes, their everyday experience in the lab rather presents as a form of engineering. Consequently, a lot of them cited specific problem-solving (such as finding the cause of unexpected signals as I did in Sec. 3.2) as a bigger motivator for staying in experimental research than the discovery of fundamental truths about nature (surely also because the "truth" that can be discovered in specialized experimental physics setups is so niche, that it seems almost detached from concepts such as the world overall). II. At the same time, upon inquiry, most people replied that they nonetheless assume their work to explore "real phenomena" and see this as a basic feature that makes physics interesting or relevant in the first place. The notion of reality contested by these physicists remained vague: Most of them acknowledged that the access of physics to the real is limited, be that because of a mathematics-based modelling of the world that remains in some way contingent as it can coexist with

I would argue that the attempt to interpret quantum mechanics has been the attempt to describe or define exactly this relationship between what we call quantum objects or quantum phenomena[2] and reality — a question that is answered differently depending on the type of interpretation chosen. In order to illustrate this claim, we shall briefly return to the EPR-paper [33] that provided the original motivation for the development of the Bell-inequality as introduced in Sec. 3.4. The title of this paper is "Can Quantum-Mechanical Description of Physical Reality be Considered Complete?" with completeness here hinting at the authors' argument that quantum theory must eventually be extended by so-called hidden variables.[3] However, the title seems to further imply that, for the authors, this issue is ultimately tied to the question of whether quantum mechanics relates to *reality* in the right way. Their claim can be summarized as follows: Physical reality is introduced as "objective" and must therefore be independent of any theory describing it. Physics, on the other hand, is a practice or science that tries to describe or model the entirety of physical reality by proposing physical concepts (such as the concept of single photons) and relating these to physical quantities. A criterion of what qualifies as a "real physical entity" in a theory which characterizes it through a set of physical qualities is then given as follows

> "If, without in any way disturbing a system, we can predict with certainty (i.e., with a probability equal to unity) the value of a physical quantity, then there exists an element of reality corresponding to this physical quantity." [33, 777]

As this passage illustrates, reality is a concept that must entail some features making it possible to distinguish the real from the unreal when talking about the concepts or entities introduced by a theory. In this way, the correspondence between the description provided by a physical theory and "physical reality" itself acts as a quality factor for a theory given. However, the nature of this correspondence is closely tied to the notion of reality that is provided. This fact can be seen in the EPR-paper in a later passage, in which they write: "Indeed, one would not arrive at our conclusion if one insisted that two or more physical quantities can be regarded as simultaneous elements of reality *only when they can be simultaneously measured or predicted*. (...) This makes the reality of P and Q depend upon the process of measurement carried out on the first system, which does not disturb the second system in any way. No reasonable definition of reality could be expected to permit this." [33, 780] with P and Q being two physical quantities with non-computing operators of the second

other models, or because physics is a science performed by humans and therefore necessarily includes the position of a subject exploring the world from a subject position. I am mentioning this anecdotal collection of answers because I find it relevant for this work to at least acknowledge the positions of (experimental) physicists when talking about their discipline. I do not believe that these positions have to be adopted by philosophers without further question; but I do believe that interdisciplinary work requires a certain degree of accessibility for representatives of both subjects. Only in this way, philosophy of science of or of physics in particular can avoid accusations of trying to intervene in the practice of either discipline which seems to be a necessary conditions in order to speak of interdisciplinary collaboration in the first place. The alternative are positions which try to limit the relevance or integrity of either subject, whether that be in the form of physicists claiming that philosophy is dead and can be replaced by science entirely or in the form of philosophers trying to talk down the eligibility of physical research by treating it as a naive phantasm.

[2] Certain structural realists, such as French [32], have suggested that objects should no longer play a role in science at all. For reasons of simplicity, I will continue to use the more common conception of physical objects as present in the vast majority of literature on the subject. I, however, do not believe my argumentation to be fundamentally incompatible with the position of structural realists per se. The usage of "physical object" shall therefore not be read as taking a position in this debate.

[3] This claim is what later motivated Bell to develop a (initially hypothetical) test for whether the proposed local structure of hidden variables was compatible with the predictions provided by quantum theory [27, 14].

system.[4] The "reasonable definition of reality" is not specified further, however, when reading the text closely, it becomes clear that it does implicitly entail an appeal to locality[5] which the authors seem to find integral to any definition of reality in physics. Obviously, when we believe that entanglement is real in the sense that measurements on one of two spatially separated system can in fact change the other system no matter the distance between them, we disagree with the statement that this is an unreasonable way of understanding real objects: Instead the notion of reality that we adapt is simply non-local in the sense that the interplay between locality and causality works somehow differently.[6]

This brief discussion should provide us with a basic insight into the problem at hand: Physics has historically always worked with a notion of reality, quite similar to the version of reality provided in Einstein, Podolsky and Rosen [33], that seems to be in conflict with certain predictions or certain concepts proposed by the formalism of quantum theory.[7] Solutions to this problem can be as follows: Either, the predictions or concepts implied by quantum theory are denied to correspond to real entities (meaning that quantum theory is either false or, at the very least, incomplete because it only describes part of physical reality while leaving out others, as suggested by the EPR paper) or our notion of reality is false and we have to work on a new understanding of what "being real" really means. Most of the common interpretations of quantum mechanics fall in one of these categories: Everettian, Copenhagen-like and Conciousness-dependent interpretations provide examples of varying radicalness of what new notions of reality could look like by abandoning certain features such as determinism and introducing new ideas such as "many worlds" or a dependence of reality on a conscious observer. Hidden-variable or epistemic interpretations of the wave-function on the other hand preserve a classical notion of reality and claim that incoherences are caused by a flawed formalism limited in its access or correspondence to what is really going on. A third solution would be to take an anti-realist stance on physics overall, meaning that the original claim that physics is supposed to entail descriptions of real entities is either weakened or denied.

4.1.1 Physicalism

Having established this relevance of questions about reality for physics, it should further be noted that the EPR-paper mostly speaks of "Physical Reality" instead of reality per se. I want to mention this detail as I believe it to bring attention to the relevant fact that physics does not try to describe any phenomena or objects that could be considered real in every meaning of the word but instead limits itself to the full description of a certain set of "real" things. This statement might be contested by certain physicists who advocate for a strong form of reductionist physicalism in which only objects explored by the natural sciences and the qualities recognized by these disciplines can act as markers of reality overall. I reject such a notion of reality on the basis of two arguments: One is the pragmatic

[4] I do take a certain familiarity with the EPR-paper for granted here and will therefore not elaborate further on the content of the proposed thought experiment.

[5] The locality that is being adhered to here means that systems can only be influenced by their immediate local environment, hence the statement "which does not disturb the second system". For a more detailed discussion of these notions of locality and separability by Einstein, see [34].

[6] It is because of this that it is sometimes said that Bell disproved "local realism". The specifics of this term are, however, rather unclear which is why I did not adapt it for this thesis and instead remained vague in the discussion of the implications of the violation of the Bell inequality as seen in Sec. 3.4. For more details on "local realism", see for example Myrvold, Genovese and Shimony [35].

[7] Many of these features specific to quantum mechanics such as superpositions and entanglement were explored in this thesis. For a more complete view and an analysis of Einstein's advocacy for a realistic interpreation of quantum mechanics, see Santos [36].

argument made in Footnote 1, stating that for the sake of this work, the practice of both disciplines involved shall not be disregarded as meaningless. Since philosophy is famously very much interested in entities that explicitly transcend the category of physical beings (hence the word metaphysical), I do not see how, from a very strict physicalist perspective, interdisciplinary work between physics and philosophy would even be reasonable and therefore, this thesis could simply end here.

Secondly, I believe this view to be removed from empirical evidence beyond the brief moments in which we engage with reality strictly as scientists. There are, for example, scientists who believe in God and do not see their practice as scientists in contradiction with their religious belief, since God is not included in the physical reality that they are trying to explore through their research. While this example may not be convincing to hardcore reductionist physicalists, what can be said about religion can in this case also be said about the belief in numbers as real entities, about moral truths, or about the aesthetic dimension of experience.

We can, for instance, engage with music as a natural scientist. A symphony can be analyzed as vibrations in air, measurable frequencies, and neuronal responses. Yet such a physical description does not account for the reality of the music as it is heard — its expressiveness, its capacity to move or console us. These aspects of reality, even though they are not real in the same sense as for example electric fields or photons, are nonetheless genuine features of our world. They remind us that reality, as we encounter it, cannot be reduced to its physical substrate without losing essential dimensions of meaning and truth.

4.1.2 Anti-realist views of physics

On a similar basis, the anti-realist approach to physics introduced as third solution to the question surrounding quantum theory and reality shall be rejected for the scope of this thesis. Saying that physics does not engage with reality is very much in opposition to what the stated goal of most physicists is.[8] While one could argue that they still engage with *something*, just not physical reality (we could for example assume that physicists share a common delusion and instead explore the laws of this delusion or, alternatively, the laws of their own minds that created it), this would deface the meaning of practicing physics to an extent that would eradicate its qualification to be called physics in the mind of most of its representatives. Instead, physics would be downgraded to a sub-discipline in denial, e.g. of psychology or philosophy. Since, in this thesis, we want to take both disciplines seriously in terms of their stated goals[9] and at least assume limited success in meeting these goals (thereby qualifying as serious scientific or academic disciplines in the first place), this courtesy shall be extended to physics as well. Despite this pragmatic argument, I further also believe an anti-realist approach to science to be removed from the everyday experience that especially modern science is extraordinarily successful in shaping our lives, e.g. through technology. If physicists were completely wrong about what they were doing, it seems unlikely that the laws discovered by them could lead to intentional and repeated changes in the physical world. The only other plausible explanation of this success of modern physics is seemingly to deny not only the grasp of physics on a form of any

[8] I do not necessarily include what we could call non-realist theories such as instrumentalism in this definition as for these, the case presents as slightly more difficult. For reasons of limited time and space, we shall not explore the subtleties of this debate further.

[9] Of course, taking "a description of physical reality" as the stated goal of physics is an argument prima facie. We shall, nonetheless, use it for the scope of this thesis due to its simplicity and anecdotal agreeableness, and leave the further discussion and empirical exploration of this question to other people.

reality but instead the existence of physical reality as we experience it outside of labs and universities overall.[10]

4.2 How reflect on physics?

The remarks made so far can be summarized as follows: When taking physics seriously as a science that has the objective of exploring physical reality through mathematical theories, a conception of what this reality entails has relevance to its success. This means that from a notion of reality, criteria can be formulated that make it possible for physicists to distinguish between concepts introduced by their theories that correspond real structures in the world and concepts that are merely features of a mathematical formalism. While we can accept that the physical world itself is objective in the sense that it exists independently of our understanding of it[11], notions of reality are subject to change as the example of quantum mechanics illustrates. Debates surrounding quantum mechanics have tried to address this issue by either limiting the extent to which quantum theory describes reality (meaning that certain features of it, such as "superpositions" or "entanglement" must necessarily be unreal) or by calling for a redefinition of what "being real" means in physics and introducing additions to or and denying certain characteristics of the former conception of reality in physics, known as classical.

A solution to this problem seems to no longer fall into the scope of physics as "notions of reality" can hardly be treated as a part of physical reality itself. Therefore, engaging in questions of this kind means philosophizing. But similarly to physics, philosophy is not a monolith and its methods are manifold. We may therefore ask how we should go about addressing the matter in a way that respects the boundaries set above, namely, to refrain from falling into a form of anti-realism about physics or adapt a form of reductionist physicalism that disqualifies philosophical research respectively.

In the second part of this thesis, I intend to propose *phenomenology as a philosophical method* that can engage with questions surrounding quantum phenomena and reality without dictating a new definition of reality to physicists that is not connected to their practice. I will begin by introducing the pillars of this methodological understanding of phenomenology in Sec. 4.2.1. In Chapter 5, I will present the example of the London-Bauer-French interpretation to show that phenomenological approaches to quantum physics have been successfully attempted in the past. Using this example, I will illustrate what I believe to be the advantage of a philosophical approach inspired by phenomenology in the context of debates surrounding quantum theory. In Chapter 6, I will try to extend these considerations by introducing the idea that science as a mode-of-being in a phenomenological sense is not only different from other contemporary modes-of-being but instead also subject to a process of change over time. I will map out this understanding of science using the example of the single-photon source built in the first part of this thesis. Finally, I will conclude with a brief discussion of the overall content of this thesis.

[10] Once more, this depiction of anti-realist takes on science is simplified. We shall accept it for now on the basis that this simplification comes with a certain accessibility to physicists as well as philosophers. Despite, the argument presented here is simply the criterion that for the rest of this work, anti-realist interpretations of physics shall not be acceptable. Even if one disagrees with this limitation, this does not challenge the validity of the arguments to follow on a fundamental level.

[11] We shall discuss the concept of objectivity in greater detail in Sec. 5.1.

4.2.1 Phenomenology as a philosophical method

The phenomenological tradition is diverse. The term is most commonly associated with Husserl who originally adopted it from the work of Franz Brentano on descriptive psychology. However, Husserl believes the epistemic questions of philosophy to vary greatly from what would fall into the realm of psychology, meaning that he intends phenomenological analysis to be a way of studying the structures of consciousness explicitly beyond the empirical approach of psychology [37, 14ff].[12] Already within Husserl's work, the role of phenomenology does not remain fixed but develops from a tool necessary to explore the foundations of pure logic into what Husserl calls a "rigorous science" on its own whose main method consists of a number of reductions that intend to grant access to phenomena in their pure form [38, 4]. However, Husserl is by far not the only philosopher claiming to practice phenomenology: Other philosophers such as Martin Heidegger and Maurice Merleau-Ponty reinterpret the word for their own philosophical projects.

To fix a common ground between these different lines of thought is not a simple task. For the scope of this thesis, rather than adhering to a single phenomenological tradition, we will instead adopt a provisional working definition based on five main features. The purpose of the features chosen for version of phenomenology as a method for philosophy of science will be elaborated through the discussion of the afore mentioned examples (the French-London-Bauer solution to the measurement problem and an analysis of the experimental approach taken in the implementation of the heralded single-photon source). For now, we can say that our definition shall simply be based on the following points:

1. *The unity of conscious experience*: Phenomenology, literally meaning the study of phenomena, deals with the way things appear to us in experience. Studying this appearance instead of the objects has the advantage of dissolving issues relating to the relationship between the subject and the object or the "I" and the world. Instead of having to wonder whether the subject has the ability to access things belonging to the world around it and how this reference might work in detail, we accept that in experience, such a relationship is already established.[13] By working phenomenologically, we can investigate this relationship in the unity in which it always presents itself, by acknowledging that a division of this unity into an object and a subject is already an abstraction.[14]

2. *Goals of phenomenological research*: Of special concern to the phenomenologist are the structure

[12] This important distinction might be rather hard to grasp at first glance. It can, therefore, be helpful to at least briefly understand it within Husserl's philosophical framework of consciousness and intentionality: In [37, 19], Husserl writes: "Sofern aber jedes Bewußtsein 'Bewußtsein von' ist, schließt das Wesensstudium des Bewußtseins auch dasjenige der Bewußtseinsbedeutung und Bewußtseinsgegenständlichkeit als solcher ein." Phenomenology as the study of conciousness in this way does therefore not reduce *conciousness of something* to either studies the subjective workings of the mind (as e.g. psychology would) or to a study of the "Gegenständlichkeit" of the things that appear to us. We can rediscover these points in my definition of phenomenology as a philosophical method for this thesis in 1. *The unity of conscious experience*.

[13] See e.g. Claesges et al. [39, II] and Heidegger [40, 52ff, 205ff]

[14] To physicists, such an approach might seem unnatural as their practice usually focusses on the object-side of this relationship that they try to isolate from a potential subject. This difference is useful to us, as it gives further justification why a philosophical treatment might be uselful for certain questions in the first place — as Crease [41] puts it:"The scientific stance, in brief, involves objectifying what is being studied, while the philosophical/phenomenological stance is to examine the engagement between the scientist and what is being studies" [41, 52]. Similarly, cutting off the other pole of this relationship and thereby "objectifying the subject" as psychology can be understood to do does not fulfill the requirements of phenomenology either (as explained in Footnote 12).

of experience and its conditions. This structure might vary depending on the type of experience; at the same time, varying types of experiences also have different premises that must be fulfilled in order to make such an experience of the world possible in the first place. Following Crease [41, 53], we can illustrate this using the picture of a "frame": Working in the lab requires framing our experience of the world in a way that makes it possible to perform measurements on the objects appearing in it [41, 56] (instead of e.g. engaging with the world as the place in which we live our everyday life or experiencing it as an inspiration to produce art). As phenomenologists, looking at these framings, as well as the phenomena that certain ways of framing the world give rise to, allows us to find the characteristics of different domains of reality.[15] In these different domains, it is not only the phenomena that differ, but it is also the way in which we are, our mode of being in the world, that is different [41, 55] [40, 113f].

3. *Method*: The core feature of the methodology of phenomenological practice can be understood by taking "a fresh approach to the concretely experienced phenomena" [38, 10]. This thesis stays true to this requirement through its analysis of the heralding SPS in Ch. 6

4. *Intersubjectivity and the lifeworld*: Experience is always related to the certainty of inhabiting a world constituted by multiplicity of objects together with other subjects or conscious beings [42, XIII][40, 117ff]. While we can approach this world in different ways (science being one of them), the way we engage with it in our everyday life is of special relevance as it provides the background out of which other ways of engagement can develop.[16] Therefore, any phenomenological approach must account for this special role of what Husserl calls "lifeworld" and contain a description of intersubjectivity which demarcates it from the solipsism of other philosophical frameworks such as certain versions of empiricism [39, II].

This list does not claim to account for the entire philosophical range of phenomenology in a historical sense. However, it provides a framework within which certain philosophical traditions such as the Husserl interpretation put forward by French fall while also living up to the afore mentioned conditions on a philosophical understanding of science within this interdisciplinary work. Why exactly that is, will be discussed further briefly in Sec. 5.2 and further in the Conclusion 7. For now, we shall turn to an example to see how philosophical method can be applied to quantum theory and what kind of results it manages to produce.

[15] Compare this to Claesges et al. [39, II].

[16] For an illustration of this claim, see once more Crease [41, 55] or also [40, 66f].

CHAPTER 5

First phenomenological approaches

In 1939, the two physicists Franz London and Edmond Bauer published a short text discussing their take on the famous measurement problem under the title "La Théorie de L'Observation en Mécanique Quantique".[1] This text is often read as a reformulation of the von Neumann interpretation in which the abrupt termination of the superposition in the measurement process is assumed to be caused by the consciousness of the observer [43, 482]. Interpretations of this sort are rather unpopular with the vast majority of physicists [44, 9]. This should draw our attention to a concept not discussed so far that seems to play an important role in physicists' understanding of their discipline – namely the role of objectivity.

In Sec. 5.1 of this chapter, I will therefore briefly recall the measurement problem and highlight its ties to questions of objectivity in quantum physics. Based on this discussion, I will formulate a third criterion for philosophical approaches to the measurement problem in the form of a rejection of subjectivist positions. In the second part of this chapter (Sec. 5.2), I will recite the position of the philosopher Steven French who argues that the London-Bauer booklet should be read as attempt to understand the measurement problem phenomenologically. Following French, I will relate some of their arguments to Husserl's philosophy and therebyshow that French's interpretation of Bauer and London's position respects the criteria for philosophical approaches to physics, namely the rejection of anti-realist and subjectivist position.

5.1 The measurement problem

As argued in Ch. 4.1, a core problem of quantum mechanics is that it is in conflict with some of the features formerly thought to be constitutive to physical reality. I briefly illustrated this issue using the EPR-paper and the problem of locality. However, another commonly discussed issue is connected to the assumption that physical reality is generally thought to be objective, meaning independent of the minds of sentient beings or subjects.[2] While, unlike the clear-cut contradiction between the calculations (and latter tests) provided by Bell and Einstein locality, this statement is not directly in

[1] The text was available to me in French and I will therefore be quoting from the French original. However, translations can be found in the Appendix in Sec. A.5

[2] This point is also explicitly mentioned in the EPR-paper's first sentence: "Any serious consideration of a physical theory must take into account the distinction between the objective reality, which is independent of any theory and the physical concepts with which the theory operates." [33, 777] (*emphasis added*).

disagreement with the predictions of quantum theory, the issue of objectivity is nonetheless often brought up in the context of quantum measurements.

To understand this connection, we shall take a brief look at the special role measurement holds within quantum mechanical formalism. For reasons of simplicity, I will follow the account provided by London and Bauer [45, 40–41], which I believe to be a fair representation of the issue at hand: Let us assume that we want to measure a quantity $F(x, p_x)$ of a system in a mixed state[3]. A full description[4] of this state is given by the wave function $\Psi = \sum k\psi_k u_k(x)$ with u_k being the eigenfunction that is associated with a certain value f_k of F. Usually, in order to perform such a measurement, we make use of a measurement apparatus which we assume to also believe to be in possession of an observable $G(y, p_y)$ (this could for example be the positions of a needle) with the eigenvalues $g_1, g_2, \ldots$and their respective with the eigenfunctions $v_1(y), v_1(y), \ldots$Before measurement, we assume this apparatus in a "neutral" state of $v_0(y)$.

In order for this apparatus to be used for the measurement, a connection between the original system and the measurement device has to be established. We can model this as a coupling between the state of the apparatus and the state of the system of interest, meaning that after the coupling, their shared state can be described as

$$\Psi(x,p) = \sum k, \rho \Psi_{k_\rho} u_k(x) v_\rho(y). \tag{5.1}$$

For a good measurement apparatus, it must be the case that we can directly associate a given measurement result g_ρ to a certain value of the observable F, namely f_k. If we assume this to be true, Eq. 5.1 can simply be written as

$$\Psi(x,p) = \sum \Psi_k u_k(x) v_k(y). \tag{5.2}$$

After the coupling, the measurement apparatus and the original system are therefore now in a mixed state. However, this is not how the measurement presents to us: Instead of observing a superposition of states, the measurement apparatus very clearly ends up displaying a single value of g_k, meaning that following our logic, the originally mixed state of our system must have somehow been reduced to a pure state f_k. We can verify this by repeating the same measurement on the same system: Unless we somehow restore the superposition, the results remain the same, suggesting to us that the system is now in fact in the state $\Psi = u_k$.

The question is hence how and why this reduction of the wave-function takes place, considering that after the model provided by Eq. 5.2 the interaction with the measurement apparatus does not provide a sufficient explanation. Instead, we should be able to describe the apparatus, being a part of physical reality itself, by the formalism of quantum mechanics as being in a mixed state as well if the theory claims to be complete. If it is nonetheless the measurement apparatus that somehow leads to the collapse of the wave-function, a full description of this process would have to account for this form of interaction. It would ideally also provide an answer to the question, why a certain state is adapted instead of another one. If this process is taken to be coincidental, something would have to account for the fact that this sudden collapse happens in the case of measurement and not elsewhere (for a comprehensive and more detailed overview of these issues, see for example Myrvold [46]).[5]

[3] I am using the term "mixed state" here since this was the word used for superpositions at the time. One should, however, not confuse it with what we usually call a mixed state nowadays, namely a statistical mixture of pure states.

[4] For the sake of the argument, we shall assume a Ψ-ontic interpretation here. For the reasons that London and Bauer provide for this assumption, see London and Bauer [45, §3]

[5] Some of the physicists that I talked to about this issue suggested decoherence as a possible solution. I do not want to go

I do not plan to provide a definitive answer to this issue or take position on the different suggestions that have been made to solve it, other than the approach of London and Bauer as described in the next section. Instead, this reminder should for now simply provide the background to the statement that to certain physicists and certain philosophers, the measurement problem can only be solved by paying attention to the role of the conscious observer. The conscious observer enters the picture, since, depending on our understanding of the measurement problem, we might look for a factor in the measurement process that can cut the "chain of correlations". As previously stated, if we assume the quantum mechanical description to be a complete theory, anything physical should be described by its formalism and therefore be a part of this endless coupling of mixed states. However, depending on our understanding of the mind, consciousness is not part of this physical reality. Hence, some interpreters of quantum mechanics such as von Neumann believe it to be reasonable to place the so-called "Heisenberg cut" exactly here, diving the world into the observer and the observed [43, 480ff].

As already mentioned in the beginning of this chapter, many physicists take issue with suggestions of this kind. This seems reasonable to me based on the understanding of physics that I previously suggested: If we take physics to be science that is trying to provide a full description of physical reality, a fundamental feature of this reality has always been objectivity in the sense of an absence of any dependency on the subject. [6] Suggesting that the outcome of experimental processes can in the end only be fully understood by taking reference to something that is not part of objective physical reality therefore potentially fails physicists in two different way: It either suggests that their original project of describing physical reality on its own is set up for failure to begin with since the existence of physical objects is somehow related to something that does not fall into this domain of the physically real; or it undermines the adequacy of experimental observation for the project of physics, thereby completely robbing it of its empirical basis.

Based on the claim made in the beginning of this part, that for the sake of interdisciplinarity such major interferences into the practice of either discipline involved will not be accepted for the scope of this work, positions of this kind must be disqualified. I will call this third criterion (in addition to a rejection of reductionist physicalism and anti-realist positions on science developed earlier) the rejection of subjectivist attempts to interpret or discuss either the measurement problem or the entirety of quantum theory.[7] I reference subjectivism instead of objectivism here, since the latter would have to potentially appeal to a certain conception of objectivity. As we will later see, perspectives on objectivity differ. Rather than ascribing to a certain definition of what objectivity entails, I therefore instead use the weaker formulation of anti-subjectivism, meaning that the subject

into further detail on this issue and instead rely on the reader's own research about this point. It should, however, not go unmentioned that it is highly debated whether decoherence provides answers to the problem at hand, explaining why the measurement problem is still a point of contention nowadays.

[6] The attempt to provide a description of reality that abstracts from any of the subjects involved e.g. in the experimental process is therefore a core feature of scientific research in this field. This point is raised in order to illustrate, how deeply engrained this assumption is into the practice of physics.

[7] I understand that me rejection of these position is here limited to a methodological argument. Another strong argument can however be made when looking at observer-independence as the agreement of different subject on the same outcome: The fact that several observers can agree on one outcome of a measurement (e.g. in the form of: the needle points up) seems to be a good basis for the assumption that some type of objectivity must in fact exist. However, this claim is based on the premise that these other subjects in the first place and the acknowledgement that their experience of the world has a similar status as my own. I will come back to this point when discussing the form of objectivity proposed by Bauer and London and the relationship to intersubjectivity in the philosophy of Husserl.

may not play an integral role for constitution of physical reality and that its entities are therefore not contingent upon human consciousness or observation.

5.2 The French-London-Bauer interpretation

Equipped with this new criterion, we must treat the Bauer-London text differently to how Jammer [43, 482] reads it as a reformulation of the von Neumann position (otherwise, it would automatically disqualify). Luckily, an alternative reading is provided by French. To portray his position, I will mainly rely on one of his early texts, namely French [47] on the topic. I however, believe the core arguments made in it to be in line with later texts such as French [48].

French's main claim is that the London-Bauer interpretation is usually misread since its phenomenological background and the consequent specific use of certain vocabulary is not taken into consideration. The idea is based on the fact that London was in fact familiar with the early phenomenological movement (meaning mainly the work of Husserl) and received a doctorate in philosophy himself for a work that was published in the "Jahrbuch für Philosophie und phänomenologische Forschung" [43, 482]. Keeping this in mind, we shall turn to the first sentence in the text in which London and Bauer move from an explanation of the measurement problem to their own interpretation. In the French original, this sentence reads

> "Mais un couplage, même avec un appareil de mesure, n'est pas encore une mesure. Celle-ci est achevée seulement lorsqu'on a observé la position de l'aiguille. C'est précisément cet enrichissement de connaissance, acquis en vertu de l'observation, qui donne à l'observateur le droit de choisir entre les différentes composantes du mélange par la théorie, de rejeter celles qui ne sont pas observées et d'attribuer dorénavant à l'objet une nouvelle fonction d'onde, celle du cas pur qu'il a trouvé." [45, 41]

This is the passage that is commonly interpreted to advocate for a conscious-dependent collapse of the wave-function, as French points out as well [47, 483]. However, London and Bauer specify the reason for this right of the observer to choose ("le droit de choisir") between different versions of the wave function by relating it back to her ability to establish objectivity by separating herself from the mixed state that she should technically be a part of:

> "L'observateur a un tout autre point de vue: Pour lui c'est seulement l'objet x et l'appareil y qui appartiennent au monde extérieure, à ce qu'il appelle « objectif ». Par contre il a *avec lui-même* de relation d'un caractère tout particulier: il dispose d'une faculté caractéristique et bien familière, que nous pouvons appeler la « faculté d'introspection »: il peut se rendre compte de manière immédiate de son propre état. C'est en vertu de cette « connaissance immanente »qu'il s'attribue le droit de se créer sa propre objectivité, c'est-à-dire de couper la chaîne de coordinations statistiques (...) en constatant: « Je suis dans l'état w_k »ou plus simplement: « Je vois $G = g_k$ »ou même directement: « $F = f_k$ »." [45, 42]

To French, it is in particular this passage about the characteristic capacity of introspection that suggests that London and Bauer do not try to argue that it is actually the observer that is causing real and physical change to the system (and therefore the wave function). Instead, French suggests that they look at the situation at hand not as physicists but as phenomenologists [47, 484]. This means, that from the perspective of a physicist, this situation is fully described by an extension of the wave function since, speaking from the perspective of a physicists who approaches the world with the intention of describing it entirely as a physical system, the fact that the observer is simply a part of this physical reality seems evident.[8] Looking at the situation in this way, therefore simply find an extended wavefunction

$$\Psi(x, y, z) = \sum_k \psi_k u_k(x) v_k(y) w_k(z) \tag{5.3}$$

with w_k representing the state of the observer that is now coupled to this mixture [45, 42]. However, if we want to understand why we are confronted with the phenomenon of a discrete measurement result that appears in connection to our act of measurement and what this tells us about the relationship between us, the observers, and the quantum entity that appears as the object of our observation, the right way to approach this question is to approach it phenomenologically. From this perspective, in which we start of by taking the impression of the observer seriously without asking about the nature of the world around him, we can see that the consciousness in which the collapse-phenomenon is experienced is structured by its ability to introspect [49, 35f].[9] This ability leads to the separation that constitutes the object as an object (or in other words, separating the object from the unity of the phenomenon is an act that objectifies it).

We should keep in mind that the form of objectivity that London and Bauer speak of here ("Objectivement, - c'est-à-dire *pour nous* qui considérons comme « objet »" [45, 42]) is not the same as the objectivity that I spoke of earlier when discussing the features of a conscious-independent reality.[10] However, French points out that the creation of objectivity in this new sense (meaning to separate the object- and the ego-pole of our experience) is a very fundamental feature of observation per se [47, 484]. We can see this, by accepting 1.*The unity of conscious experience* of the phenomenology-definition that I provided in Sec. 4.2.1 and then adding that a separation of these unitary phenomena begins, whenever we happen to begin reflecting on them: It is in this way, in which experience that we just live through turns into a new type of experience that we call observation [47, 485], e.g. by saying that "The car is red", attributing the property of redness to the object side, and "The color has a weird taste to it because I have taken LSD." In this act, the ego-pole (I) is necessarily separated from the side of the object (the car) since we want to judge the object's objectivity ("Gegenständlichkeit") and gather potential information on the mode of our experiencing by keeping track of our own state [49, 36–38]. Looking at these operations of our consciousness from the perspective of phenomenology, we are provided an "analysis of this act and uncovering (...)) of this separation" [47, 485] that we otherwise would have not been able to identify as a key structure of observation in general.

Seen in this light, we can also note that the observation of quantum objects does not differ greatly from the experience of observation in any other situations: Instead of giving the observer a special role in quantum theory, the project of London and Bauer seems to rather be to point out that observation always contains the special act of separating or cutting off the object –– it is simply the case that in quantum mechanics, this feature becomes more evident as, for reasons which will I further discuss later, it forces us to reflect on the observer in relationship to the phenomenon.

To the physicists who take issue with such a description and prefer to stay within the lane of physics rather than turning into phenomenologists, London and Bauer provide the afore hinted at

[8] Relate this e.g. to [49, 31]

[9] To Husserl, this is a form of experiencing oneself that is inherent to the "I". [49, 30].

[10] In German, we would probably translate objectivity in the sense in which it is referenced here by London and Bauer as "Gegenständlichkeit" – we find this word also in the writings of Husserl. For this, see for example Husserl [49, 36]

alternative:

> "(...) on a par conséquent toujours le droit de négliger la réaction sur l'appareil du « regard »de l'observateur; et, remontant le cours du temps, on obtiendra des conclusions certaines sur l'état de l'appareil (...) et, par suite, de l'objet avant l'observation (*mais, bien entendu, après leur couplage*)." [45, 49]

It is this passage, that allows us to relate back their account to objectivity in the former sense (meaning as existing independent of the mind): French points out that, in phenomenology, certain forms of experience do not offer this opportunity to disregard the role of the observer since their "very *existence* is guaranteed by the regard" [47, 487]. However, London and Bauer seem to be of the opinion that this is not the case for the objects that we are confronted with during quantum measurements, meaning that the role of the observer and therefore the perspective of the observer can be neglected by simply returning to a description such as the one provided in Eq. 5.3, in which the observer as an observer does no longer appear and instead, is just treated as yet another physical object. The opportunity for this change of perspective that Bauer and London describe as equally valid ("on a (...) *toujours* le droit..." [45, ibid] – emphasis added by me) is why their account does not pose an invalidation of the criterion of anti-subjectivism as I developed in Sec. 5.1. Instead, a purely physical treatment of the same phenomenon remains valid.

The reasons that force us to speak of the observer therefore lay outside of the physical process. This fact is what leads us to have to investigate the measurement process no longer purely through the means of physics since physics is not equipped to reply to questions concerning things that are not physical objects in the first place. As French puts it: "There simply is no possibility of describing the observer in this sense in quantum mechanical or any other physical terms – indeed there never was." [47, 486].

Nonetheless, the fact that a physical treatment remains valid does not yet assure to us that what we are treating through our formalism is in fact a real phenomenon and not an event that only takes places within our own, deserted mind. Within Husserl's phenomenology, this fear of solipsism is anticipated and solved through what we can call constitutional intersubjectivity. This means that for Husserl, the experience of intersubjectivity is anchored within the structure of our consciousness and it is based on this experience of the other that we can begin to perceive the world objectively [50, 120ff].

Similarly, Bauer and London also bring up intersubjectivity in relationship to a potential solipsism in their text. They write

> "Et pourtant, nous savons qu'en réalité les relations de physicien entre eux n'ont pratiquement pas changé depuis la découverte de la mécanique quantique; ils ne sont pas enfermés chacun dans un isolement solipsiste, ils se servent des mêmes moyens d'échange scientifique qu'autrefois et sont capables d'étudier en commun le même objet." [45, 49]

and later add

> "La possibilité de faire abstraction de l'individualité de l'observation et créer une conscience scientifique collective ne saurait donc être mise sérieusement en question." [45, 49]

While this argument does not go into the depths of Husserl's analysis about the constitutitive nature of intersubjectivity for the notion of an objective world, it provides an example of the secondary, real experience of this intersubjectivity that will resonate with any real-life physicist: It is the experience that the access to the phenomena they are trying to research is shared with others and that it is this communal experience that is taken as evidence for why their discipline seems to be dealing with "real objects" instead of subjective phantasms.[11]

Within the context of (Husserl's) phenomenology, this experience is not denied but instead validated by the fact that intersubjectivity in the abstract sense of an experience of the other is in fact the first step towards the constitution of an objective world from the perspective of a subject [50, 123]. Physicists might ask why such an approach is even necessary as to them, the existence of an objective world is already obvious. This certainty is, however, exactly what phenomenology is trying to explore and question in regard to its validity. Luckily enough (for physicists and phenomenologists alike) the result of this exploration, at least for Husserl, is positive and therefore, no contradiction between a phenomenological approach and the existence of a real world with real physical objects is to be found [50, ibid]. Therefore, we can say that a phenomenological approach is at least compatible with a realist approach to physics and the empirical evidence London and Bauer implicate, points towards the assumption that physics is also successful in its venture to access physical reality through its means.

As we have seen, the phenomenological reading of the London-Bauer interpretation stands up to my criterion of a realist understanding of physics and is also not subjectivist in the sense that it claims physical processes to rely on the mind or consciousness. The solution that London and Bauer suggest for the measurement problem within physics might be somehow controversial, since a fully physical description of the measurement process would according to them require a continuation of the superposition into the observer. However, they also give reasons why from a phenomenological standpoint, the cutting of this chain is justified if we take the observer to not simply be another physical object but take into consideration his special position as a conscious subject.

What remains insufficiently addressed by London, Bauer, and French is the question of why it is specifically within quantum physics that doubts concerning the role of the observer emerge. After all, observation as a conscious process is not specific to quantum experiments; instead, it is also the basis of classical experiments performed long before quantum mechanics was even developed. We shall turn to this difference between the experience of quantum and classical phenomena in the next chapter and investigate it further.

[11] Hence the criterion that the results of experiments must be re-creatable by others – a notion that is still true for quantum experiments, albeit it in a slightly modified sense.

CHAPTER **6**

Quantum experience

As we have seen in the previous chapter, something within quantum mechanics seems to make us turn towards questions regarding the observer. I have given a tentative explanation of this appearance of the observer within in the context of the measurement problem. The approach of London and Bauer, however, rejects this explanation by stating that the observer does not appear in quantum-mechanical processes to a larger extent than it does in classical measurements, in which the experimentalist is also simply treated as a physical object which we try to abstract from in the measurement data by including him as a potential source of error or disturbance in the measurement apparatus.

There must therefore be a reason outside of physics for this peculiarity. Let us once more turn to the differences between classical and quantum physics to explore this idea further. London and Bauer address it briefly at the end of their paper, where regarding classical physics, they state that

> "En physique classique, on peut se représenter à chaque instant un système de manière univoque et continue par l'ensemble de toutes ses propriétés mesurables, même pendant qu'il n'est pas soumis à une observation, et c'est précisément la possibilité de cette continuité de connexion entre propriétés et objet qui fut considérée en général comme une preuve que la physique s'occupe de quelque chose de « réel »(...)" [45, 49]

Further, they acknowledge that for quantum, this relationship of properties and the object, their carrier, changes. They write

> "En mécanique quantique un objet est porteur, non pas d'un ensemble défini de propriétés mesurables, mais seulement d'un ensemble de statistiques « potentielles »se rapportant à ces propriétés mesurables, statistiques qui entrent seulement en vigueur à l'occasion d'une mesure effective, bien définie. Si l'on fait abstraction de toute mesure, il est dénué de sens de se représenter ces propriétés mesurables comme réalisée; la forme mathématique même de ces statistiques ne le permet pas." [45, 49f]

Such a notion of properties in the context of quantum mechanics redefines not only the way in which properties function, but once more also our understanding of "the real" itself since the former conception of continuous properties seems to a fundamental characteristic of things falling under our understanding of reality. We shall return to this later.

For now, as I have announced earlier, I will attempt a clarification of the issues regarding the role of the observer by taking the phenomenological plea seriously and "turn back to the things themselves".

May the things in question be the phenomena explored in this thesis. If we want to explore the conditions of their appearance — I have previously called the "framing" — one way is to describe and systematize the context in which they appear: the experiment.

In order to gather a general understanding of how experiments are performed within quantum theory, we shall adopt a notion similiar to that which is popular in modern operational approaches to quantum theory: Here, the quantum mechanical measurement process is defined by three stages — state preparation, transformation and measurement. An alternative description is provided by Margenau and Park [51], who instead propose the three stages of *state preparation*, *state determination* and *measurement*. However, Margenau admits that it is a particularity of quantum physics that the second step of state determination works differently from what we can expect in classical physics. We can illustrate this using the example of a very banal classical experiment such as the fall of a ball from a certain height. Let us say that we want to determine the force which a ball falling from a platform of 10 m enacts when hitting the ground at 0 m. For the actual measurement, we use a forcemeter of some kind that we install on the ground. *State preparation* would now take place in the form of somehow elevating the ball to a height of 10 m. We can verify the state (*state determination*) of the ball before the actual measurement by performing two preliminary measurements — one verifying that the ball is in the beginning indeed at a position of 10 m from the ground and one testing the force that it enacts on the ground before the fall has taken place (so in its "starting position"). These measurements that determine the state of the ball before the actual experiment resemble the means by which we determine its state after the measurement, in which we would make sure that the ball does indeed arrive at the ground-level of 0 m and measure its force at the moment in which it is hitting the ground.[1]

When trying to experiment using quantum objects, this process presents differently. Let us, for example turn to the source of polarized photons as used for the Bell tests in Sec. 3.4. "State preparation" is achieved by placing the BBO-crystal into the beam of the pump laser. The state that this is supposed to create is the superposition in Eq. 2.8 — but this can not directly be confirmed to us before the final measurement as a previous determination would destroy the superposition in question. We therefore have to find a way of measuring the state indirectly. This is, however, not the only difficulty facing us: Since even an indirect way of measuring the state of the superposition would not be able to confirm its state indefinitely. We can relate this difficulty back to the account of the measurement problem in Sec. 5.1: As we have established there, measurements always yield discrete results. A direct measurement of a superposition is not possible as for this, a measurement apparatus would have to be able to present this potentiality of having two different states somehow. However, measurement apparatuses present classically not as possibilities but instead as having definitive properties as described in the above cited quote by London and Bauer. This means that for our source of entangled photons, we would always receive the result that at the moment of determination, the state of the ensemble is either $|VV\rangle$ or $|HH\rangle$. While this result is valid for the description of the state at this moment of *state determination*, it does not hold up for a true determination of the actual state of the ensemble which we believe to be a mixture of $|VV\rangle$ and $|HH\rangle$. Margenau and Park [51] acknowledge this in their paper: They state that in quantum physics, a state can only be determined through repeated measurement.

Another peculiarity that results from the behavior of quantum objects is a potential confusion

[1] Of course, we could think of more complicated examples in which this would not exactly be the case. Either way, within classical mechanics we are usually able to determine the state before the experiment by performing a single measurement.

between state preparation and measurement, which Margenau and Park [51] address too. We can once more illustrate this using the other source that was used in this thesis, the heralding SPS. A particularity of heralding is that the single photon state is in a way "prepared" through the measurement of the idler photon as we have seen in Sec. 2.2. While Margenau and Park [51] argue against this notion and rather advocate for the view that instead of a preparatory measurement, it is a selection of measurement data that takes place, I would contend this view by pointing out that the notion of a preparatory measurement is in fact closer to the formalism. Of course, as we have seen, the formalism can be interpreted and the reality of its content can be contested. However, in our attempt to find a phenomenological description of the measurement process, we should acknowledge that the formalism does at least play a role as part of the background under which quantum phenomena can appear to us or "be experienced" in the form of an observation.

To understand this, we shall return to the picture of the framing that I used in Sec. 4.2.1 in order to illustrate point 2. *Goals of phenomenological research* of my phenomenology definition. The framing can be understood in the sense of a horizon that is necessary for the phenomenon to appear in the first place. It is typical for framings of this kind that they are not obvious to us at first sight. Instead, they provide a form of quiet background to the phenomenon which is what is appearing to us "in the foreground".[2] The framing therefore requires careful further investigation and the formalism of quantum mechanics can be used as a tool that points towards the framing of quantum physics since it suggest to us a form of understanding the single and repeated measurements of quantum states by introducing the possibility of a superposition.

What kind of framing of reality does the formal representation of a superposition point towards to? A hint has been provided to us by London and Bauer in the quote cited above: Here, London and Bauer suggest that quantum objects have the particularity of no longer being the carriers of definitive properties such as the ball in the example of the classical experiments. Instead, they appear to us as carries of possibility, a fact that is represented in the formalism through its use of literal possibilities in a mathematical sense. It is only in this way that we can make sense of the notion that quantum phenomena "appear" to us at all since the singular experiences themselves, taken without the context that what we allow to appear to us are actualizations of possibilities, remain classical and discrete.

In his paper [53], Damiano Sacco comes to a similar result. He summarizes these findings by suggesting that "the phenomenon appears in quantum mechanics according to two different modalities": One is in the form the discrete measurement results which is however different from classical results in the sense that it is not reproducible. This points towards the second form of appearance of quantum phenomena which he describes as "the projection onto the world of a horizon that does *not* lie in the domain of actuality – but rather in that of potentiality" [53, 510]. To me it seems that it is within this horizon of potentiality that a quantum world can appear to us at all. Thus, the quantum experiment provides to us not only a new form of physics but also a new form of experience "of potentiality" [53, 511].

It is also in this context of potentiality in which we can understand why it is suddenly the observer that appears to us in the measurement process or why all of the sudden questions regarding his role emerge even though he was actually present all along: As we have seen, the observer himself as an abstract "I" can be understood as a derivate of the unitary phenomenon. If the context, the premises or the "framing" of the phenomenon change — if the the phenomenon itself changes, it should be of

[2] Compare this to Heidegger [52]

little surprise that the function and the appearance of the observer change too. Therefore, Sacco [53, 514f] argues that what he calls the subject-site (meaning the place within an experiment in which the phenomena appear) is also split through the splitting of experience according to the previous paragraph: On one hand, we tie the notion of a singular subject particular to a singular experience, similar to the description provided in Sec. 5.2 in which the subject is the necessary opposite pole to the object. However, on the other hand, the framing of the single phenomenon that enables us to see it within the horizon of potentialities suggests a subject that also exists within these possibilities itself. I would argue that it is, at least partly, this new understanding of a subject of possibilities that causes irritation in the observance of quantum phenomena since it draws our attention to the fact that it is also the subject which has to — in some sense — be actualized.

CHAPTER 7

Conclusion

While the first part of my thesis is devoted to the investigation of single photons and their behavior in a range of experiments, my second part focusses on the (philosophical) interpretation of the observed (quantum) phenomena. The motivation for such a structure is to provide an example of true interdisciplinary collaboration between both disciplines beyond the usual procedure, in which philosophers talk about physicists — but not to them.

I believe such an interdisciplinary approach to be valuable for both disciplines, philosophy and physics, in the following ways: To philosophers, it offers an honest opportunity to analyze the process of quantum measurements while still respecting certain bounds (an example of which are the criteria that I presented within this thesis) in order to find a philosophical approach that does not invalidate scientific practice. To physicists, it offers answers to questions that often arise within their practice but, in some ways, transcend it. Such an approach further brings them to reflect on the silent assumptions, such as the notion of reality, that always accompany their work.

For this form of interdisciplinary work, I have suggested phenomenology as a philosophical method since it allows philosophers to investigate the questions that they care about (namely in this case role of consciousness and the validity of knowledge gained through (scientific) experience) and equally respects that for physicists, the conscious observer is simply another physical object.[1] Applying this approach, I have come to the following conclusions:

I. For the impression that the act of observation seems to reduce the wave function, the phenomenological approach of French, London and Bauer (Ch. 5) has provided reasons that are grounded in the structure of observation by which they answer questions that seem not only to be of interest for philosophers. Instead, I would argue that the vast discussion of the measurement problem by the developers of quantum mechanics shows that to many physicists, the apparent relevance of the observer in the measurement process is also a source of worry.[2] By granting validity to the way conscious observers experience and describe the measurement process, without claiming that this is relevant to the physical process happening independent of their observation, a phenomenological

[1] We can see from this, if it was not yet clear already, that phenomenology does not promote a form of physicalism either. Therefore, my third criterion is automatically respected.

[2] The reasons for this concern are likely to be similar to the reasons I presented against a subjectivist interpretation in Sec. 5.1, namely the fact that this role of consciousness could potentially rob physics of its methods or gravely limit the possibility of its aspirations.

approach addresses the concerns of these physicists while also taking them seriously in their role of conscious observers, that is, as humans.[3]

II. Regarding the question of why we are drawn to the observer in this way when confronted with quantum phenomena, I have proposed in Ch. 6, building on the work of Sacco, that this is due to a change of the subject's constitution. Through an analysis of the heralding single-photon source, we have seen that there are peculiarities in quantum phenomena which turns the experience of them towards the realm of possibilities. Since the phenomena have changed in such a fundamental way, the subject as their counterpart in experience must consequently change too.

I would like to conclude my thesis with two remarks that go beyond the conclusions I elaborated so far. One regards the discussions about reality, which I undertook in Ch. 4, and the other the role of the observer in the quantum mechanical framework, considered in Ch. 5.2 and Ch. 6.

(i) Acknowledging the fact that philosophers and physicists approach quantum phenomena from different perspectives, we may be now able to close the gap between our (classical) understanding of reality and the predictions and concepts that quantum theory applies. I will therefore propose, binding together the results of the second part of my thesis, a collaborative two-fold process. On one hand, it is the task of philosophers to provide a broad notion of reality and answer questions relating to it such as "How can we know that anything outside of our own mind even exist?", "What does this reality entail overall?" and "What are the parts of reality that can righteously be investigated through the means of which science?" As a suitable framework to such questions, London and Bauer suggest phenomenology. [4]

However, as shown by the example of locality, phenomenology in the way that Husserl practices is does not really produce the more pragmatic definition of physical reality that physicists need in their practice. In my opinion, this more applied notion of reality should instead be developed in close relation and on the basis of already established scientific practice.[5] This enterprise can and should be supported by philosophers of science who, equipped with the vocabulary of broader philosophical enterprises, reflect together with physicists on the properties of the entities and concepts already

[3] It should be said that in this way, London and Bauer do not provide an answer to the questions raised in Sec. 4.1 concerning a specific notion of reality suitable to include quantum objects (the other option that I provided in that section to neglect that quantum theory describes something real in the first place is rejected by them in the beginning of their paper, where they state that they believe the wave function to be a full description of the state of system — see London and Bauer [45, 22]). While they do make some remarks concerning the difference between the association between objects and the properties that such an object definitely or potentially holds, as we have seen in Ch. 6, these comments do not seem sufficient to for example also account for the different notions of locality as discussed in Sec. 4.1 and investigated in Sec. 3.4.

[4] London and Bauer seem to acknowledge that these questions are beyond their work when writing: "Ce qui précède se rattache à un problème philosophique important, que nous ne pouvons pas aborder ici: déterminer les conditions nécessaires et suffisantes pour qu'un objet de pensée soit doué d' « objectivité », c'est-à-dire puisse devenir objet de science." [45, 50] ["The above relates to an important philosophical problem, which we cannot address here: determining the necessary and sufficient conditions for an object of thought to be endowed with « objectivity », that is, to become an object of science."]

[5] This might be somehow surprising, as I have previously introduced the relevance of such a notion of reality for the scientific practice itself. However, the example of quantum phenomena prove in my opinion that physics does somehow manage to use broader markers of reality such as the intersubjective criterion of shared perception to do research that does no longer fall into the criteria used to qualify real entities previously.

treated as real phenomena in practice.[6] For such a collaborative effort, I still believe phenomenology to be of use *as a method* since its plea to go "back to the things" ensures a reflection-process that stays relatable to physicists.

(ii) I acknowledge that in particular my last chapter (Ch. 6) is potentially of less interest to the practice of physics. I nonetheless believe that considerations of this kind are worthwhile since they give us a perspective of physics broader than the everyday experience of calculations or bringing the experiment to function. Looking at physics in this way does no longer only present physics to us as a practice that is trying to describe, model, understand and research real physical objects. Instead, it reveals physics to us as a way of approaching and experiencing the world that is particular to it — in short: as a way of being. The change that has taken place between classical physics and the development of quantum mechanics has a complex multitude of reasons ranging from the developments of new technologies to the progress in mathematics. We should, however, acknowledge that through such changes our experience of the world is subject to change to an equal extent and that vice-versa, it is our mode of being that can influence the type of technologies that are developed. An exploration of this reciprocal relationship is far beyond the scope of this thesis. With this last part, I simply want to point towards the idea that an interpretation of physics in this sense, meaning as a relationship to the world that creates a certain version of the world for itself, a specific domain of reality, is worthwhile. I was not be able to provide such a phenomenological analysis of physics pointing towards an exploration of being in this work. However, I believe an understanding of it even more pressing when the role of science in our lives is changing as rapidly and the relationship of many non-scientists to science becomes increasingly difficult as they see their domains of reality to be threatened by its all-encompassing success. It is in particular in these moments in which we should ask what science actually is: not only for the sake of its own practice but also in order to understand it as a human enterprise among others, in order to understand how it is subject to change, where this change is headed and how its becoming alters the world. Even though in Chapter 6, I have sometimes quoted Heidegger, I do not want to suggest any particular framework for such an undertaking. Nonetheless, I believe a historicization of phenomenological to look promising. For now, I shall leave the further exploration of these ideas to others.

[6] We can illustrate this using an example taken from this thesis: Even though superpositions or entities such as "single photons" are already contributed a realistic character when we work with and on them in the lab. Obviously reflection on such entities and concepts can also work as a corrective here. An example for this is e.g. the debate over the use of the word "photon" - for more on this see Lamb [54].

APPENDIX A

Appendix

A.1 Characterization measurements

A.1.1 Laser characterization

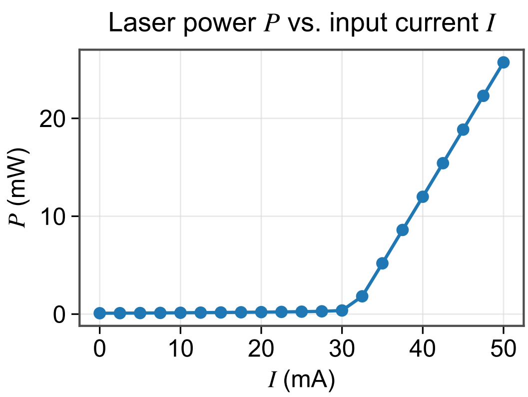


Figure A.1: Characterization of the laser power in relation to the input current I. Power measured at a distance of 30 cm.

A.1.2 Single photon detectors

Dead time

The dead times of the detectors were measured by plotting the auto-correlation (this means a histogram binning signals of the detector in question according to the time difference between signals). The dead time then corresponds to the first maximum of this graph.

Table A.1: Dead times of the detectors of the kits (all Thorlabs *SPDMA*). The last detector was broken at the time at which this measurement was performed. The detectors without a label ('Used as') were not employed in this thesis.

Serial number	Used as	Dead time (ns)
M01230312	Det T	22
M01233616	Det A	27
M01233615	Det B	27
M01230311	-	37
M01230310	-	28
M01233614	-	Detector broken

Dark counts and background light

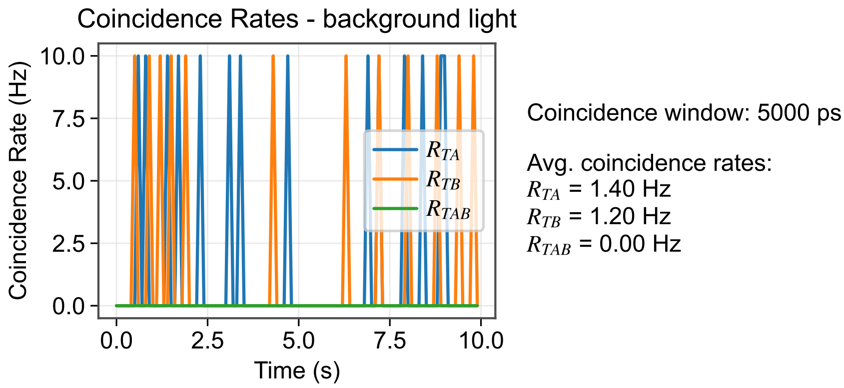


Figure A.2: Dark count rates with the detector's completely shielded from external light; measured for 10 s.

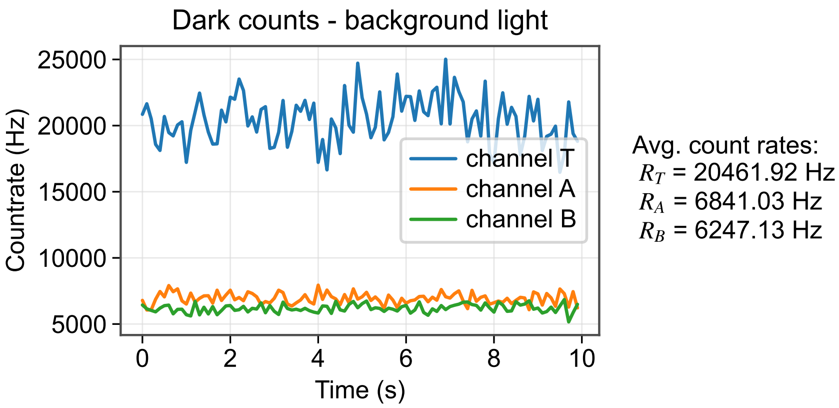


Figure A.3: Count rates of the three detectors with only the usual background lighting on. Measurement performed for 60 s.

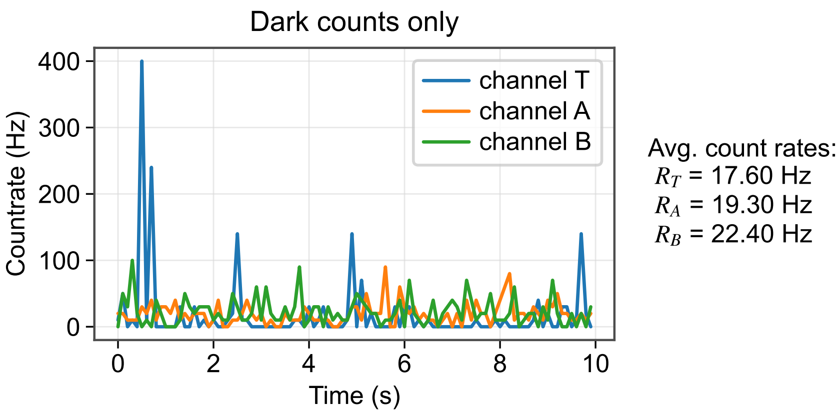


Figure A.4: Depiction of the coincidence rates of the three detectors with only the usual background lights on. Measurement performed for 60 s, same data used as for Fig. A.3.

A.2 Measurement data - Interferometer

We can calculate the wavelength Tab A.2 this using the formula

$$\lambda = 2\Delta x = 722\,\mathrm{nm} \tag{A.1}$$

We shall assume an error of 0.02 µm since for certain peaks, alternate position of the maximum within this distance were detected. Therefore, the overall error on the average count rate is 0.028., leading to an overall error of 50 nm.

We can further also calculate the wavelength from the fit parameters in Fig. 3.12. For this, the wavelength can be calculated using

$$\lambda = \frac{4\Pi}{b} = (737.8 \pm 0.7)\,\mathrm{nm}\pm \tag{A.2}$$

Peak	Count rate	Piezo position (µm)	Distance to next maximum (µm)
1	22443	6,21	
2	22335	6,55	0,34
3	22508	6,93	0,38
4	22127	7,29	0,36
5	22117	7,67	0,38
6	22080	8,03	0,36
7	22157	8,39	0,36
8	21412	8,74	0,35
Average distance			0,361428571

Table A.2: Maxima of the count rates in different piezo positions, taken from Fig. 3.11.

with the error calculated using the error on b as given in Fig. 3.12.

It should be obvious that both results do not correspond to the expected value of $\lambda = 810\,\text{nm}$. This suggests to us that the piezo calibration must be wrong since the detectors have band pass filter included in their detector optics, which would not transmit photons of the here calculated wavelengths. While this does not change the qualitative results that an interference pattern appears and while it seems reasonable that this interference is still caused by the single photons, considering that we are using the coincidence rate R_{TB}, this still causes and issue with the overall x-axis scaling that can no longer be trusted. Sadly, this problem was noticed too late within my writing process to include a correction measurement of the piezo steps. However, we can say that the problem is most likely that the values passed on to the piezo either through the kit software or python code, do not correspond to the distance that it actually ends up travelling. This could be confirmed by recording the interference pattern of light with a known wavelength.

A.3 Measurement data - Bell

$\mathbf{Pol}_T$(°) \ $\mathbf{Pol}_A$(°)	22.5	67.5	112.5	157.5
0	2811.85	733.35	246.70	2259.20
45	2199.35	2742.10	997.25	421.75
90	270.05	2421.55	2953.05	817.05
135	880.55	456.80	2217.80	2612.05

Table A.3: Coincidence rates R_{TB} measured without the kit software for different polarizer setting (Bell test): Recorded at maximum iris aperture of 12 mm.

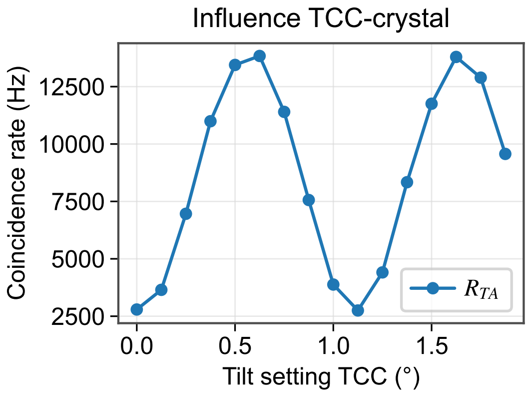


Figure A.5: Influence of the rotation of the TCC-crystal in the pump laser on the coincidence rate R_{TA} with Polarizer T set to $-45°$ and Polarizer A set to 45°. The sinusoidal form is due to the changing phase $e^{i\phi}$ between the vertical and horizontal polarization components. The graph therefore confirms, that the TCC crystal is able to shift this phase difference. Due to the change of basis into $|A\rangle$ and $|D\rangle$, a minimum in this graph is selected for perfect alignment in the $|H\rangle$-$|V\rangle$-basis.

Pol$_T$(°) \ Pol$_A$(°)	22.5000	67.5000	112.500	157.500
0.00000	515.400	130.900	41.0000	440.700
45.0000	419.100	491.900	155.600	79.9000
90.0000	50.6000	414.900	474.900	121.700
135.000	143.500	64.5000	382.200	476.000

Table A.4: Coincidence rates R_{TB} measured with the kit software for different polarizer setting (Bell test): Iris aperture (2.0 ± 0.3) mm, $S = 2.572 \pm 0.019$.

Pol$_T$(°) \ Pol$_A$(°)	22.5000	67.5000	112.500	157.500
0.00000	1773.40	426.900	179.800	1513.60
45.0000	1397.30	1556.50	505.100	300.100
90.0000	168.000	1367.30	1613.70	412.900
135.000	531.300	252.900	1307.30	1594.30

Table A.5: Coincidence rates R_{TB} measured with the kit software for different polarizer setting (Bell test): Iris aperture (3.3 ± 0.3) mm, $S = 2.510 \pm 0.010$.

Pol$_T$(°) \ Pol$_A$(°)	22.5	67.5	112.5	157.5
0	5073.40	1198.50	517.60	4287.20
45	3844.90	4320.00	1429.60	917.10
90	457.20	3839.80	4433.10	1189.30
135	1693.50	691.80	3452.10	4530.20

Table A.6: Coincidence rates R_{TB} measured with the kit software for different polarizer setting (Bell test): Iris aperture (4.6 ± 0.3) mm, $S = 2.453 \pm 0.006$.

$\mathbf{Pol}_T$(°) \ $\mathbf{Pol}_A$(°)	22.5	67.5	112.5	157.5
0	6993.60	1608.80	890.00	6370.30
45	5532.30	5860.00	1948.80	1477.00
90	733.50	5322.90	6247.70	1668.00
135	2551.80	1102.50	5169.60	6637.50

Table A.7: Coincidence rates R_{TB} measured with the kit software for different polarizer setting (Bell test): Iris aperture (5.9 ± 0.3) mm, $S = 2.410 \pm 0.005$.

$\mathbf{Pol}_T$(°) \ $\mathbf{Pol}_A$(°)	22.5	67.5	112.5	157.5
0	12623.10	3272.90	1479.60	11154.70
45	9574.90	10792.80	4009.70	2723.50
90	1280.00	9703.50	11749.60	3192.60
135	4492.50	2215.90	9156.10	11705.00

Table A.8: Coincidence rates R_{TB} measured with the kit software for different polarizer setting (Bell test): Iris aperture (7.2 ± 0.3) mm, $S = 2.339 \pm 0.004$.

$\mathbf{Pol}_T$(°) \ $\mathbf{Pol}_A$(°)	22.5	67.5	112.5	157.5
0	15463.0	4014.50	1760.30	13551.7
45	11634.4	13087.3	4967.80	3452.80
90	1555.20	11994.0	14433.6	3955.80
135	5810.80	2983.90	11211.8	14069.2

Table A.9: Coincidence rates R_{TB} measured with the kit software for different polarizer setting (Bell test): Iris aperture (8.0 ± 0.3) mm, $S = 2.300 \pm 0.003$.

A.4 Additional data

A.5 London-Bauer: Translated quotes

Remark: The quotes in this section are the translated quotes of the French original of the London-Bauer-paper (Ref. [45]). For the translation, DeepL was used as remarked in the AI-inventory. Some of the translations were further adjusted by me.

Translation of Quote 1 on page 52:

> "But coupling, even with a measuring device, is not yet measurement. Measurement is only complete when the position of the needle has been observed. It is precisely this enrichment of knowledge, acquired through observation, that gives the observer the right to choose between the different components of the mixture by theory, to reject those that are not observed, and to henceforth assign the object a new wave function, that of the pure case he has found." [45, 41]

Translation of Quote 2 on page 52:

> "The observer has a completely different point of view: for him, it is only the object x and the apparatus y that belong to the external world, to what he calls « objective ». On the other hand, he has a very special relationship *with himself*: he possesses a characteristic and well-known faculty, which we may call the « faculty of introspection »; he can become immediately aware of his own state. It is by virtue of this «immanent knowledge »that he grants himself the right to create his own objectivity — that is, to cut the chain of statistical correlations (...) by stating: « I am in the state w_k », or, more simply: « I see $G = g_k$ », or even directly: « $F = f_k$ »."[45, 42]

Translation of Quote 3 on page 54:

> "(...) we therefore always have the right to neglect the reaction of the apparatus produced by the observer's « gaze »; and, by going back in time, we will obtain certain conclusions about the state of the apparatus (...) and, consequently, of the object before the observation (*but, of course, after their coupling*)." [45, 49]

Translation of Quote 4 on page 54:

> "And yet we know that in reality, relationships between physicists have hardly changed since the discovery of quantum mechanics; they are not locked away in solipsistic isolation, they use the same means of scientific exchange as before, and they are able to study the same object together." [45, 49]

Translation of Quote 5 on page 54:

> "The possibility of disregarding the individuality of observation and creating a collective scientific consciousness cannot therefore be seriously questioned." [45, 49]

Translation of Quote 6 on page 57:

> "In classical physics, a system can be represented at any given moment in a unique and continuous manner by the set of all its measurable properties, even when it is not being observed, and it is precisely the possibility of this continuous connection between properties and objects that was generally considered proof that physics deals with something « real »(...)" [45, 49]

Translation of Quote 7 on page 57:

> "In classical mechanics, an object is not considered to be the carrier of a defined set of measurable properties, but only a set of « potential »statistics relating to these measurable properties, statistics that only come into effect during an actual, well-defined measurement. If we disregard all measurements, it makes no sense to represent these measurable properties as realized; the very mathematical form of these statistics does not allow it."[45, 49f]

APPENDIX B

AI Inventory

Name / Model	Area of application	Sections	Example prompts
ChatGPT (GPT-5)	LaTeX formatting: • Finding specific LaTeX commands • Formatting tables • Fixing errors in LaTeX	No specific section	• *"Please include more horizontal spacing in this table."* • *"How can I make this symbol in Latex: (...)"* • *"How can I fix this compiling error: (...)"*
	Python programming: • Adapt code structure to different contexts • Combine pieces of self-written code (fix variable names etc.) • Debug code • Write small standardized functions (e.g., create LaTeX table output, calculate averages) • Structure code	Figures in Ch. 2 and Ch. 3	• *"Can you include this function (...) into this code (...) and replace the plot part at the bottom by it."* • *"Can you help with this error message: (...)."* • *"Can you write a function to calculate the $g^{(2)}$-function based on this formula: (...)."* • *"Please remove any unused parts from this code: (...)."*
	Literature research and citation (in particular creating BibTex-citations)	No specific section	• *"From this book (ISBN: ...), I want to cite chapter 3. Please create the BibTex-citation for me."* • *"I am looking for the original paper, in which the CHSH-inequality was developed. Please provide me the DOI."*
	Translation / phrasing: • Translation • Looking for alternative English phrasing	In particular Ch. 4 and Ch. 5	• *"Within this sentence (...) I use 'by' twice. Can you suggest alternative ways of phrasing it."* • *"In this sentence, I want to use a word that is similar to (...) in German. Please suggest such a word."*
DeepL	Translation	Sec. 5.2	Input: Text to be translated
Connected Papers	Literature search	No specific section	Input: DOI of a paper of interest

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Acronyms

APD Avalanche Photo Diode. 19

BBO Barium Borate. 13, 32, 34, 35

GRA Grangier-Roger-Aspect. 14, 15, 19, 27

SPDC Spontaneous Parametric Down-Conversion. 5, 8–10

SPS Single Photon Source. 5, 8, 9, 11, 13–19, 22, 28, 32, 47, 59

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