Lab Manual Quantum Erasure
Quantum Technology – SK2903

Giulio Foletto
foletto@kth.se

November 2025

1 Introduction

The quantum eraser was proposed as a thought experiment in the 1980s and has undergone many variations and experimental verifications throughout the decades. It owes its relevance to the fact that it touches on many of the cornerstones of fundamental quantum mechanics in a simple scenario which can be studied without complicated mathematics, for example with the language of quantum information.

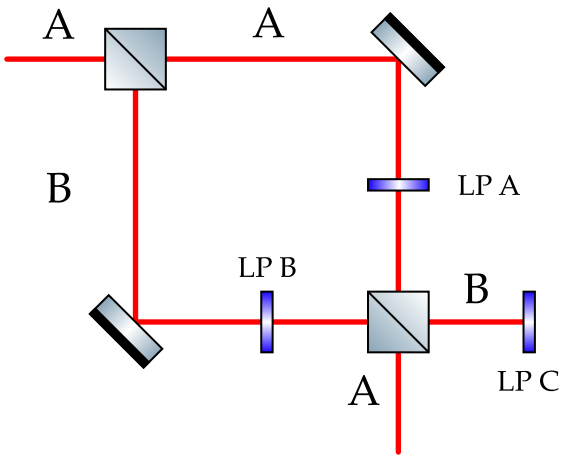

Figure 1: Schematic view of a simplified quantum eraser setup based on a Mach-Zehnder interferometer. A and B label arms inside the interferometers but also entrance and exit paths. Linear polarizers (LP) A and B can make the two arms more distinguishable, whereas LP C can erase the distinguishability.

The first concept it allows us to explore is quantum interference. The probability of an event, for example the observation of a photon at a certain output port of an interferometer, like in Fig. 1, may depend on different *configurations* of the quantum system, such as passing through either arm of said interferometer. From the standpoint of classical probability theory, one would expect this probability to be simply the sum of the probabilities of the alternative configurations. However, observations show that this is not the case: there is an additional *interference term*, which depends on the *phase between the different configurations*. In the interferometer example, this can be controlled by lengthening or shortening one of the arms with respect to the other. Although classical wave mechanics can explain this phenomenon, the language of quantum physics is better equipped to study it in depth and understand its consequences.

Quantum probability theory associates *amplitudes* to different configurations: they can take on complex values and thus be influenced by phase terms. The probabilities of the configurations are the *squared norm* of the corresponding amplitudes (Born's rule), from which the interference term emerges. For example, suppose a photon passes through a Mach-Zehnder interferometer (MZI): its quantum state can be described as a superposition of the two configurations corresponding to passing through each of

the two arms $|A\rangle, |B\rangle$:

$$|\psi_1\rangle = \frac{1}{\sqrt{2}} \left(|A\rangle + |B\rangle \right) . \tag{1}$$

Here, the amplitudes are equal to $\frac{1}{\sqrt{2}}$ because the MZI uses an ideal 50:50 beam splitter (BS). We then consider that the $|B\rangle$ arm is slightly longer than the $|A\rangle$ arm, so as to induce a phase term $e^{i\varphi}$, which is inserted into the state before the second BS as $|\psi_2\rangle = \frac{1}{\sqrt{2}} \left(|A\rangle + e^{i\varphi} |B\rangle \right)$. Finally, after the recombination, the state can be described as:

$$|\psi_3\rangle = \frac{1}{2} \left(\left(1 + e^{i\varphi} \right) |A\rangle + \left(1 - e^{i\varphi} \right) |B\rangle \right) . \tag{2}$$

If a detector is inserted in the exit path $|B\rangle$, the probability of finding the photon there is the squared norm of the $|B\rangle$ component of $|\psi_3\rangle$:

$$\Pr(det.) = \left| \frac{1}{2} \left(1 - e^{i\varphi} \right) \right|^2 = \frac{1}{2} \left(1 - \cos\varphi \right) , \tag{3}$$

which shows an interference term $\frac{1}{2} \cos\varphi$.

But this is not all! Interference is strictly connected to the *indistinguishability* between the two configurations. With the described system there is no way to ascertain whether the photon traveled through arm $|A\rangle$ or $|B\rangle$ inside the MZI. What would happen if we made these two options more distinguishable? We could, for instance, insert linear polarizers (LPs) in the two arms and align them with orthogonal polarizations $|H\rangle$ and $|V\rangle$. In this way, we would bind the arms with polarization: $|A\rangle \leftrightarrow |H\rangle$, $|B\rangle \leftrightarrow |V\rangle$. The final state would be:

$$|\psi_3'\rangle = \frac{1}{2\sqrt{2}} \left(\left(|H\rangle + e^{i\varphi} |V\rangle \right) \otimes |A\rangle + \left(|H\rangle - e^{i\varphi} |V\rangle \right) \otimes |B\rangle \right) . \tag{4}$$

Here, we are using a state that has norm lower than 1 to reflect the the fact that there is a non-trivial probability that the photon does not pass through the LPs. With this state, one can easily see that the squared norm of the $|B\rangle$ component no longer shows an interference term. Even though we are not actually measuring the polarization (but only the exit path), the simple fact that the two configurations are distinguishable makes the interference disappear:

$$\Pr(det.) = \frac{1}{4} . \tag{5}$$

Finally, we arrive at the erasure phenomenon. It is possible to recapture the interference by *erasing* the distinguishability between the configurations. In the example we are working on, this distinguishability is mediated by the polarization components $|H\rangle$ and $|V\rangle$, which can be made indistinguishable by observing the complementary $|D\rangle = \frac{1}{\sqrt{2}} \left(|H\rangle + |V\rangle \right)$ component. Indeed, if we insert a LP aligned with $|D\rangle$ in front of the detector, the probability of observing the photon is

$$\Pr(det.) = \frac{1}{8} \left(1 - \cos\varphi \right) . \tag{6}$$

Moreover, perfect distinguishability and complete indistinguishability are not the only options. There is a continuum between the two, and it can be shown that the more distinguishable the two arms are, the less visible the interference term is.

In the experiment, we will not only focus on the quantum eraser, but also familiarize with tools that are commonly used in quantum optics. In particular, we will work with a source of photon pairs and observe the effect that limited temporal coherence has on the interference visibility. We will use the former to improve the quality of our results and to get a taste of how light behaves at the single-photon level and we will characterize the latter in detail.

When light has a short *temporal coherence length*, its ability to interfere is hindered. In the above formulas, we have assumed that lengthening one arm of the interferometer means multiplying a phase term $e^{i\varphi}$ to the component that corresponds to that arm. But this would be true only if the light was described

as an ideal monochromatic plane wave. In reality, this is never the case: light always has a finite energy uncertainty. One of the consequences of this is that the phase difference between two delayed portions of the same light wave is not fixed but fluctuates: the larger the delay, the larger the fluctuations. Simplifying a bit, we could say that the phase φ does not take on a single value, but has a variance. When we observe the interference pattern, we necessarily integrate for some amount of time, during which the phase changes, and this smears the interference term until we no longer see it. In the experiment, we will measure this by observing the effect that different arm unbalances have on the interference.

2 Experimental setup

2.1 Scheme

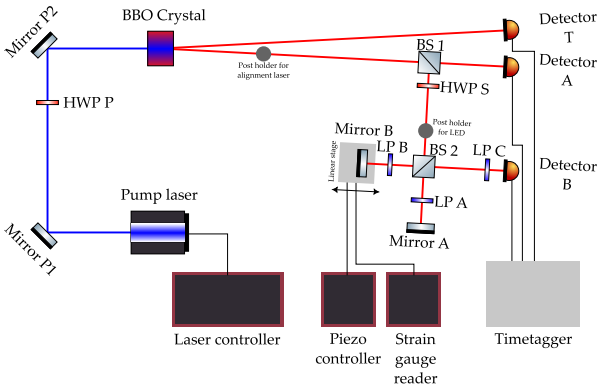

Figure 2: Scheme of the setup. BS: beam splitter; LP: linear polarizer; HWP: half-wave plate; BBO: beta barium borate.

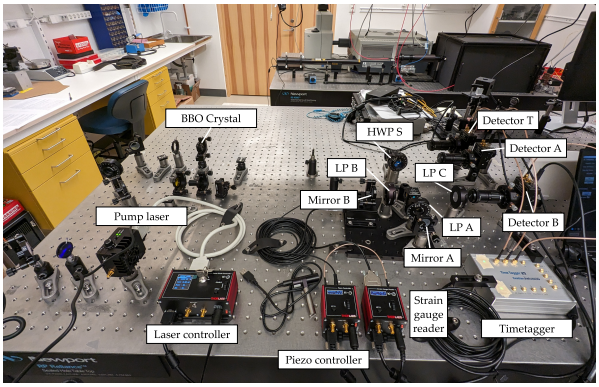

Figure 3: Photo of the setup.

Figures 2 and 3 depict and show the entire experimental setup.

Although sources of single photons are commercially available, they are very expensive and still far from perfect. Therefore, we will use a custom-built source of photon pairs based on *spontaneous parametric down conversion* (SPDC). The photons in each pair are entangled, but we will not use this: we will only use the temporal correlation between the photons in each pair to improve noise rejection.

The SPDC process is mediated by the interaction between a *pump* light field and a *nonlinear* material, in this case a beta barium borate (BBO) crystal. Some of the pump photons are probabilistically converted into pairs of photon at twice the wavelength, due to conservation of energy. In our case, we pump the crystal with a laser at approximately 405 nm, obtaining photons at roughly 810 nm. The photons in each pair are emitted at the same time, so it is easy to identify them and distinguish them from spurious events, such as photons from different pairs or background noise, by measuring the time of arrival at two detectors and discarding cases that are too far apart in time. This technique, coincident detection, improves the quality of the results and allows us to tolerate a large amount of environmental light. The photons are detected by avalanche photodiodes and their electrical signals are converted into digital time-of-arrival measurements by a timetagger.

The photons are emitted at an angle of about 3° with respect to the pump direction and travel towards detector T and BS 1. For this experiment, detector A and the transmitted path after BS 1 are unused and can be ignored. The photons that are reflected by BS 1 travel to the heart of the setup, which is a Michelson interferometer.

The geometry of Michelson interferometers is that of a cross, as depicted in Fig. 4. Light enters the interferometer through a BS (labeled 2 in our case) and travels in two arms. At the end of each, it is reflected by a mirror, and exits through the same BS. A detector is placed at the exit port of the BS which does not coincide with the entrance (detector B). The relative phase between the arms can be changed by moving one of the mirrors, remembering that the optical path is changed by twice the amount that the arm is lengthened, because light travels back and forth. In our case, the mirror in the B arm is mounted on a linear stage.

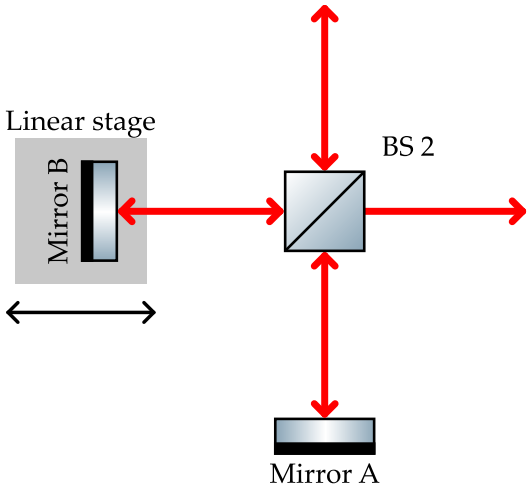

Figure 4: Schematic view of a Michelson interferometer.

2.2 Operating the setup

It is very important to obey the following safety rules when a laser source is active:

- Do not look directly at the laser beam! Never!
- Always wear protective goggles (which are provided by the lab) when the pump laser is on.
- Do not wear reflective objects such as rings, necklaces, or watches.

Instructions on how to activate and operate the different components follow. At the beginning of the session, the lab instructor will ask you to activate some of them, so you can refer to these instructions to understand how.

Pump laser: Activate with the switch on its mount and the switch on the controller. Set the laser current to 32 mA using the wheel on the controller and then enable the output by turning the key and pressing the button close to it.

Detectors: Activate detectors T and B using the switches on their side. Detector A is not used in this experiment and can be kept off. When detectors are on and the cap is removed, the main lights of the laboratory should be dimmed.

Timetagger: Activate by connecting its USB cable to the computer.

Alignment laser: USB powered, power switch on the USB plug.

LED source: USB powered.

Linear stage: Operated with a coarse adjuster, fine adjuster, and piezoelectric motor, which is controlled via software. In this experiment, you will not touch the coarse adjuster, but will operate the fine one (total range 300 µm across six revolutions) and the piezo (total range 20 µm). See Fig. 5 to identify the handles.

Piezo controller and strain gauge reader: Activated with switches on the side, operated via the Thorlabs Educational Kit software. In the Michelson tab, you can prepare a scan measurement that correlates the position of the piezo with the coincidence rate. However, changing the starting position of the scan moves the piezo even if the scan is not initiated. After turning the devices on, click on Calibrate Stage in the Michelson tab. Figure 6 shows a screenshot of the Michelson tab of the software.

Data acquisition: All data is acquired via the Thorlabs Educational Kit software, which already processes the time-of-arrival measures into more useful information such as the rate of coincident detections. Data is saved in a human-readable text format, and you will be tasked to write some code in the language of your preference to properly analyze it. Note that the separators used in the text file are not those that are expected by usual analysis programs. Although it would be easy to prevent this issue by changing some settings at the operating system level, we chose to keep them like this to remind you that data format is a common nuisance in lab experiments and we encourage you to fix this problem

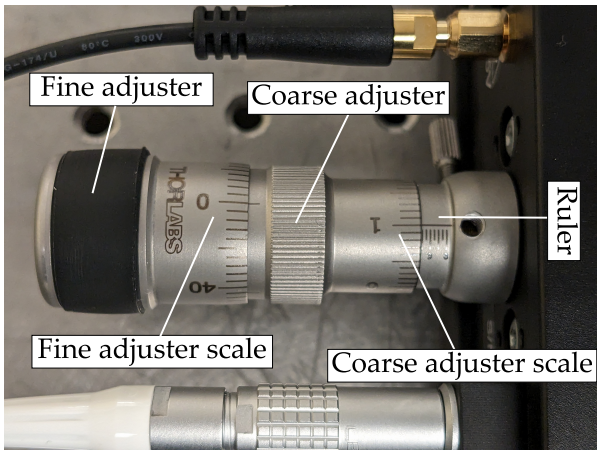

Figure 5: Photo of the linear stage adjusters.

Figure 6: Screenshot of the Michelson tab.

in your analysis code. If you need help with programming, you can ask the instructor for hints and code snippets in Python. In addition, you will be given a jupyter notebook that you can edit on the lab computer to log measurement results and perform a preliminary analysis of the data. This notebook can also be the basis for your report.

3 Experimental procedure

If they are not already on, activate the pump laser, detectors T and B, timetagger, and the controllers of the linear stage.

3.1 Coincidence settings

We define a coincident detection as a pair of detection events that happen at detectors T and B *within a short time*, but we have not clearly defined how short yet. Moreover, the photons travel different distances to get to the two detectors, and there could be further delays in the electronic chain downstream of the diodes, therefore we must add a systematic delay to the time-of-arrival measures of one detector to compensate for this.

The Delay Adjust tab of the software allows to set the coincidence window and then scan different values of the delay. After changing the settings, the Alignment tab can be used to observe the coincidence rate, and the GRA tab can be used to acquire and save the coincidence rate for some time. With these tools, we can choose the best value for the delay and the coincidence window.

1. Block arm B of the Michelson interferometer with a detector card.
2. In the Delay Adjust tab, scan the different delays with a short coincidence window, like 1 ns. Use a range between -8 ns and 4 ns and an integration time of 1 s. If the graph seems too noisy, increase the integration time and scan again. When you are satisfied, save the data to file. Log in the notebook the value Δt of the delay between detectors B and T that maximizes the coincidence rate, and set it in the appropriate field in the software (Delay B to T).
3. Move to the GRA tab of the software and acquire the detection rate for 10 s. Save the acquired data and log in the notebook the coincidence rate and the single count rates at detectors B and T.
4. In the Delay Adjust tab, set the Delay B to T to $\Delta t' = \Delta t + 20$ ns. Acquire data again in the GRA tab, save it to file, and log the same results as before in the notebook. Compare the previously obtained coincidence and single detection rate (also saved by the GRA tab) with the ones you just acquired. What is the difference? These are accidental coincidences, caused by photons that are not generated in the same SPDC event or by background light.
5. For each value of the coincidence window width between 2 ns and 6 ns at 1 ns steps, acquire and save the detection rates when the delay is set to Δt (meaning that you are observing true and accidental coincidences) and when it is set to $\Delta t'$ (so as to observe only accidental coincidences).

Log the detection rates in the notebook, which calculates for you the signal-to-noise ratio for each value of the window width.

6. During data analysis, plot the coincidence rates against the window width. Compare the accidental coincidences rate with its expected value based on the formula $R_{acc} = R_B R_T \tau$ where R_B, R_T are the single detection rates in detectors B and T, and τ is the coincidence window width.
7. Choose a width that provides a good signal-to-noise ratio and does not reduce too much the coincidence rate. Set it in the Delay Adjust tab of the software.
8. After you have completed these measurements, remove the obstacle from arm B of the Michelson interferometer.

3.2 Coherence measurement

To study the interference properties of the photons, we first optimize the alignment of the Michelson interferometer.

1. Temporarily block the pump laser with a detector card or any non-reflective obstacle.
2. Place caps on the detectors.
3. Place a white screen (that you will be given) between beam splitter 2 and detector B.
4. Insert the LED source in its post-holder and block it so that it shines light (after being connected to the computer to get power) towards BS 2. You should see a wide red light spot on the screen. The LED source has a very short temporal coherence length.
5. Set the piezo motor at 10 µm and log the initial position of the other adjusters of the linear stage.
6. Move slightly the fine adjuster. What do you see on the screen?
7. Move slightly the kinematic screws on mirror A (and only mirror A!). What do you see on the screen?
8. Try to align the kinematic screws on mirror A and the position of the fine adjuster so that the screen does not show fringes, and small movements of the fine adjuster result in large intensity swings.
9. After you have completed these measurements, log the final position of all adjusters in the linear stage.
10. Remove the LED source from the setup, remove the white screen, remove the caps from the detectors, remove the block on the pump laser path, check that both arms of the interferometer are unblocked.

In your report, give a brief explanation of what you have seen when moving the fine adjuster and the kinematic screws.

We now want to measure the coherence length of the SPDC photons, which strongly depends on the wavelength filters that are installed in front of the detectors. We will measure different interferograms. For each, you should find maximum and minimum values of the coincidence rates C_{max}, C_{min}, and calculate the visibility:

$$V = \frac{C_{max} - C_{min}}{C_{max} + C_{min}} \tag{7}$$

While in the lab, you can do this approximately by rough observation of the data and with the help of the notebook, but when you analyze the data at home you should write software to fit the pattern with a sine wave to find better estimates of maximum and minimum, and calculate V based on those.

1. In the Michelson tab of the software, perform a scan between 9 µm and 11 µm with a discretization step of 50 nm and an integration time of 1 s. You should see a interference pattern, with coincidence rates oscillating with a period of about 400 nm. Can you figure out why this is the period? This is the typical interferogram that we will measure in this experiment. Log in the notebook the maximum and minimum observed values for the coincidence rate and save the acquired data to file with the software. This file includes the position of the piezo and the coincidence rate for each position.

2. Repeat the previous point for different positions of the fine adjuster in the $[-60, +50]$ µm range around the initial position, with 10 µm steps. Remember that it is not easy to read the number of revolutions of the fine adjuster handle, so it is important that you count them when operating it. Moreover, the file does not save the position of the fine adjuster, therefore it is important that you associate each file you save with this datum, for instance by including it in the file name.

3. Observe in the notebook the position of the fine adjuster that provided the highest visibility, log it, and place the fine adjuster in that position.

Note that the notebook plots the visibility against the approximate position of the linear stage. You should see that the visibility decreases as you move further away from the initial position, which should be the point of maximum interference, if the preliminary alignment section of the experiment went smoothly. When you analyze the data at home, remember that you have to offset the positions recorded in the file with the fine adjuster position that you set manually. You should also measure the temporal coherence length, i.e., the difference in optical path length that decreases the visibility by a factor of $1/e$.

3.3 Quantum erasure measurements

We finally get to the most crucial part of the experiment! Again, we will measure different interferograms. This time, we will not move manually the linear stage, and only operate the piezoelectric motor around the point of maximum visibility. We will change the orientation of the LPs and of HWP S.

For each setting (listed below) you should perform a standard measurement procedure:

- In the Michelson tab of the software, perform a scan between 9 µm and 11 µm with a discretization step of 50 nm and an integration time of 1 s. Save the result to file. In the lab, log the maximum and minimum observed values C_{max} and C_{min}, from which V is calculated. At home, analyze the interferogram via software to fit it to a sine wave and find better estimates.
- Block alternately arms A and B, to measure the coincidence rates C_B and C_A. Use the GRA tab to acquire and save a 10 s run for each, and log the results in the notebook. Then unblock both arms.

You can set the optical elements with the following procedure:

1. Check that HWP S is set at 0° and LPs A and B are both set at 90°. Perform a standard measurement procedure.
2. Rotate LP A to 0°. Perform a standard measurement procedure.
3. Block alternately the two arms of the Michelson interferometer, and find an angle α of HWP S that balances the coincidence rate. Then, rotate HWP S to α, LP A to 0° and LP B to 90° and perform a standard measurement procedure.
4. Insert LP C between beam splitter 2 and detector B. Orient it so that the dial faces the detector. To align it, block momentarily the pump laser with a detector card, put the cap on all detectors, insert the alignment laser, and observe its reflection on the LP. Then, with HWP S at angle α, LP A at 0° and LP B at 90 degree, block alternately the two arms of the Michelson interferometer, to find an angle β of LP C that balances the coincidence rate. Finally, with LP C at β, perform a standard measurement procedure.
5. Perform a standard measurement procedure for different angles of LP C in the $[0, 90]^\circ$ range at steps of 15°.

In your report, you should comment each of these interferograms and try to explain what influences V. Specifically for point 5, calculate also the distinguishability $D = 2 \cdot \frac{\max(C_A, C_B)}{C_A + C_B} - 1$ and $M = \sqrt{V^2 + D^2}$. The variable D describes how well the measurement operated by LP C is able to distinguish between the two arms. Plot V, D, M against the LP angle and try to explain their relation.

4 Goals of the analysis

Several results can be extracted from the data recorded in this experiment. The following is a list of analysis tasks. Those marked as bonus can help improve the grade of the final (text) report but are not mandatory.

Coincidence settings

- Plot the scan of the coincidence rate against the relative delay.
- Fit it to theoretical form, extracting the best value for the relative delay and the width of the temporal distribution (bonus).
- Plot the coincidence rate which includes the signal and the accidental coincidence rate against window width.
- Compare the accidental coincidence rate with the expected one based on the rate of single counts.
- Fit the coincidence rates to the theoretical form (bonus).

Coherence measurement

- Plot the minimum and maximum coincidence rates against the position of the linear stage.
- Plot the interferometric visibility against the position of the linear stage, and fit it to its functional form.
- Extract the temporal coherence length (expressed in µm) from the fit.
- Extract the width of the wavelength filter (bonus).

Quantum erasure measurements

- Plot interferograms corresponding to the initial configurations of the waveplate and polarizers that we used in the lab.
- Plot the parameters V, D, and M against the angle of the final polarizer LP C.
- Compare the parameters with the expected theoretical form, which you can explain with ket notation (bonus).

Remember that a physical measurement is only complete if it includes an estimate of the associated error. For this experiment, estimating the statistical error is sufficient. All your raw measurements are coincidence rates, which are calculated as $R = C/\Delta t$, where C is a count of coincidence events and Δt is the integration time. Considering that the relative error on Δt is negligible compared to that on C, the error (standard deviation) on R can be estimated as $\sigma_R = \sigma_C/\Delta t$, where $\sigma_C = \sqrt{C}$. From this statistical error on the raw measurements, you can calculate the statistical error on your analyzed results using error propagation.

In the notebook report, focus on proper plots and accurate captions that explain the significance of the shown results. For the final text report, more detailed explanations are expected.