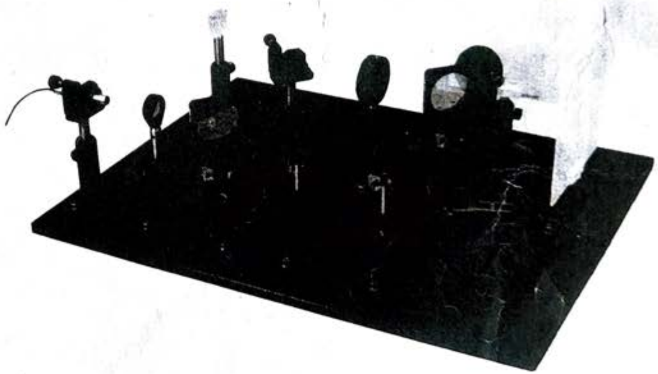
THORLABS

Discovery

EDU-QE1
EDU-QE1/M
Quantum Eraser Demonstration Kit

User Guide



Chapter 2 Safety

CAUTION

IMPORTANT: The polarizer films are covered on each side with a clear, protective film. We strongly recommend wearing gloves when assembling the polarizers so that the film is not touched with bare fingers. Avoid exposure of the film polarizers to UV light, to high temperatures, and to chemicals such as acetone.

WARNING

The laser module is a Class 2 laser. Although no protective eyewear is required around class 2 lasers due to the blink reflex, you should not look directly into the laser beam.

Chapter 3 Product Description

In a Mach-Zehnder interferometer, a beam of light is split into one of two optical paths by a beamsplitter. Due to a difference in optical path lengths between the two paths, complementary interference patterns are observed when the light is recombined by a second beamsplitter. These interference patterns are observed on two viewing screens, as the second Beamsplitter produces two combined beams.

A Mach-Zehnder interferometer is very useful in order to demonstrate the quantum mechanical properties of complementarity and the erasure of path information. If a polarizer is placed in each arm of the interferometer and their polarization planes are turned 90° to one another, the interference pattern disappears. This can be completely explained through classical electrodynamics. However, a quantum-mechanical description can also be applied if the beam of light in the interferometer reduced to individual photons (or to only an individual photon). By inserting the crossed polarizers into the setup, the two possible light paths are made distinguishable by obtaining path information. The interference pattern (wave property) and path information (particle property) cannot be measured simultaneously, since measuring the path information destroys the interference pattern.

If one adds a third polarizer between the second beamsplitter and the screen, with the polarization axis at 45° to the other polarizers, all of the photons that reach the screen once again have the same polarization. This polarizer "erases" the path information and an interference pattern is once more visible on the screen.

Rather than using single photons, as in the original quantum eraser experiment, this kit uses a green continuous-wave (CW) laser light source that emits a beam that is visible to the eye. While the outcome of the experiment can be explained using classical physics, using a quantum-mechanical description provides a perfect analogy to the single-photon quantum eraser experiment.

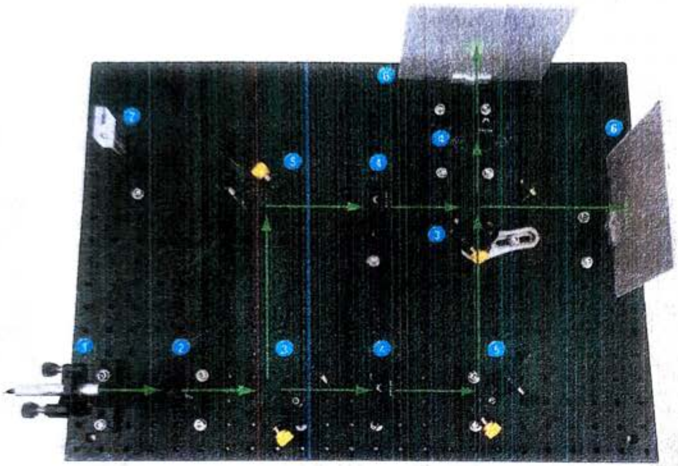


Figure 1 Mach-Zehnder Interferometer Setup and Diagram, Including (1) Laser, (2) Lens, (3) Beamsplitters, (4) Polarizers, (5) Mirrors, and (6) Viewing Screens

…etric Kit

Type	Quantity	Type	Quantity
M6 x 12 mm Cap Screw	11	M6 Nut	4
M6 x 16 mm Cap Screw	11	M6 Washer	11
M6 x 20 mm Cap Screw	4	 1 x **BD-5ML** Balldriver for M6 Screws	
M4 Screws Included with Mounts			
1 x Hex Key for M4 Screws (3mm) 0.9 mm, 1.3 mm and 2.0 mm Hex Keys contained in RSP1D/M			

4.2. Component Assembly

1. First, assemble the individual optical components and mounts. Use the 1/2" (12 mm) long 1/4"-20 (M6) screws to connect the PH3 (PH75/M) and PH2 (PH50/M) post holders to the BA1(/M) and BA2(/M) bases, respectively. Throughout the assembly, use the 5/8" (16 mm) long 1/4"-20 (M6) screws to mount the components to the breadboard.
2. Mount the ME1-G01 mirrors into two of the KM100 mounts using the setscrews on the mounts. Secure the EBS2 beamsplitters into the KM200T mounts and the LB1901 lens into the LMR1(/M) mount using the threaded retaining rings that are already placed in the mounts. Replace the lower knobs on these KM100 and KM200T mounts with the gold-colored F25SSK1-GOLD knobs by placing a hex key inside the knob and unfastening the black knob. An instructional video can be found on the web page for the KM100 on www.thorlabs.com.

Figure 2 Component Assembly Procedure

3. Mount the KM100, KM200T, LMR1(/M), and RSP1D(/M) mounts to TR3 (TR75/M) posts using the included 8-32 (M4) cap screws or setscrews, and insert them into PH3 (PH75/M) Post Holders. Put one of the KM200T posts in the PH3E (PH75E/M). Attach the viewing screens to the TR2 (TR50/M) posts using the included setscrews and insert them into the PH2 (PH50/M) post holders.

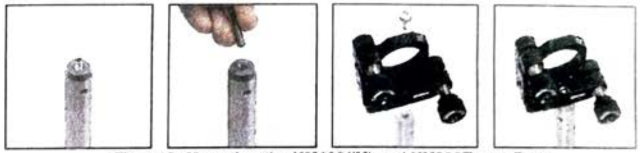


Figure 3 Mounting the KM100(/M) and KM200T on a Post

4. Screw the AT1(/M) height alignment tool on a TR3 (TR75/M) post and put it in a PH3 (PH75/M) post holder with the BA1S(/M) base attached to it.
5. The EDU-VS1(/M) screens need to be screwed onto the TR2 (TR50/M) posts. Use the PH2 (PH50/M) post-holders and the BA2(/M) bases for these posts.

CAUTION

IMPORTANT: The polarizer films are covered on each side with a clear, protective film. We strongly recommend wearing gloves and handling the films by their edges when assembling the polarizers so that the face of the film is not touched with bare fingers. Avoid exposure of the film polarizers to UV light, to high temperatures, and to chemicals such as acetone. Ensure that all three polarizers are mounted so that they are precisely parallel at 0°.

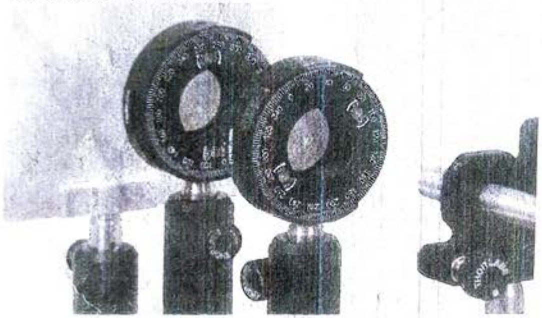
6. After removing the protective films, place 2 of the 3 LPVISE2X2 polarizer films into the RSP1D(/M) mounts and secure them using the included retaining rings. The orientation of the polarizer is indicated by its form, as shown in the image on the right. The reference flat is parallel to the polarization of the transmitted light. Instructions on how to ensure that the polarizers are mounted and aligned properly are given in the next steps.

7. Mount the CPS532-C2 laser into the AD11NT adapter using the setscrew on the side of the adapter. Place the adapter into the remaining KM100 mount, connect the laser to the LDS5(-EC) power supply, check the bottom of the LDS5(-EC) to make sure the correct voltage is used and switch it on.

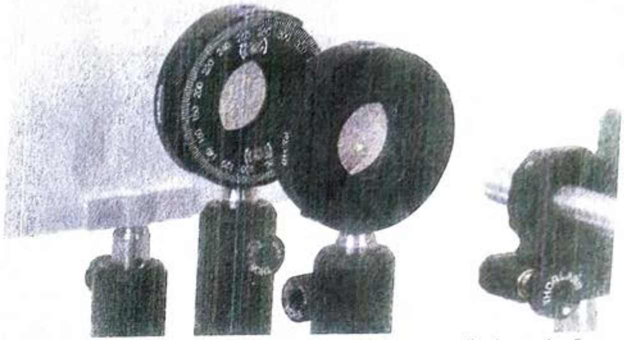
WARNING

The laser module is a Class 2 laser, which does not require any protective eyewear. However, to avoid injury, do not look directly into the laser beam.

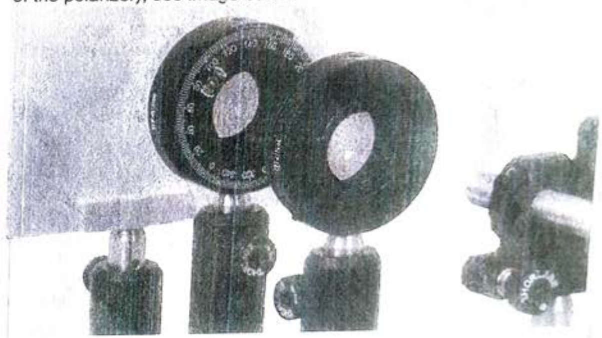
8. Place the two polarizers in front of the laser and rotate the last polarizer such that the two polarizers are perpendicular (almost no light should be passing). The orientation of the angular scale doesn't matter at this point. For example, the labels in the image below read "277°" and "34°" but the polarizers in the mounts are perpendicular.



9. Rotate the first polarizer assembly by 180° around the post axis so the labels face the other way, see image below:

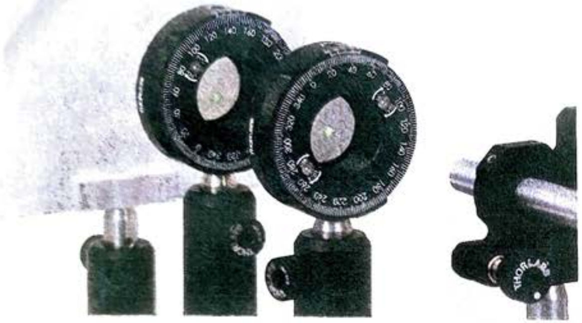


10. Rotate the second polarizer **clockwise** until it is perpendicular to the first polarizer. Note by how many degrees you turned the second polarizer (we'll call this angle φ). Make sure the transmission is close to zero (sometimes, the polarization axis of the laser causes a drop in the intensity. However, the transmission will only drop close to zero for perpendicular polarizers). In our example, the second polarizer was rotated to a position with label "143°" (note this is still a random label and doesn't say anything about the absolute position of the polarizer), see image below:

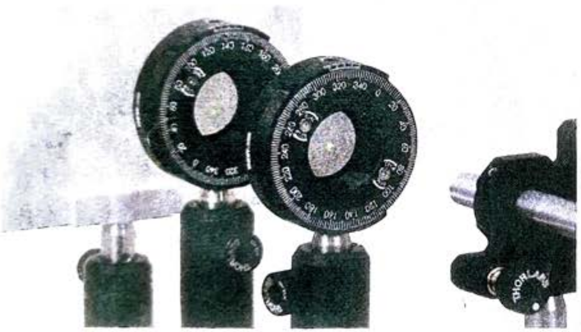


So in our case, $\varphi = 277° - 143° = 134°$

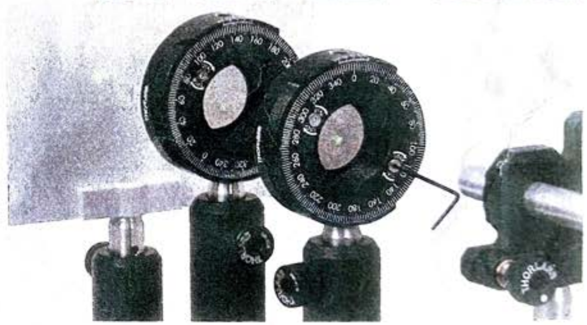
11. Now rotate the first polarizer assembly back so that the label faces the laser again.



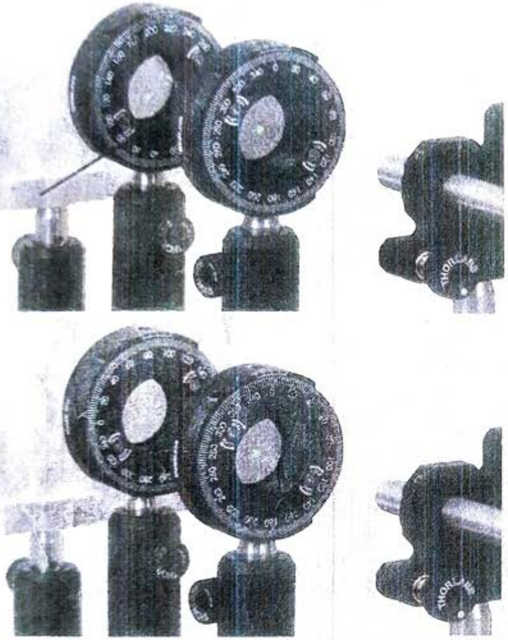
12. Turn the first polarizer **clockwise** by $\varphi/2$. In our case, the label of the first polarizer read 34°. So the polarizer needs to be turned to 34°-134°/2 = 34°- 67° = 327°, see image below:



13. We have now found the orientation of the first polarizer that is either parallel or perpendicular to the breadboard. So, in our example, the "327°" label needs to be changed to either 90° or 0°. Take the third polarizer to check whether you've found the 90° or 0° polarization (again, the reference flat is the transmission direction). Loosen the two small screws at the front of the rotation mount and turn the scale to 0° or 90°, see image below:



14. Rotate the second polarizer such that it is perpendicular to the first (so again, the transmission needs to go to effectively zero). Loosen the two small screws at the front of the rotation mount and turn the scale to 90° or 0°, see image below.



15. Mount the third polarizer and correctly set the scale on the mount using the other two polarizers, as in the previous steps.

4.3. Setup and Adjustment

4.3.1. Laser Setup

1. Attach the laser assembly to the end of the optical breadboard.
2. Check that the laser is polarized at 45° by placing a polarizer set to -45° in front of the laser and rotating the laser in the mount until minimum transmission is achieved. The transmission will not drop to zero since the laser is not linearly polarized. Then, remove the polarizer from the setup again.

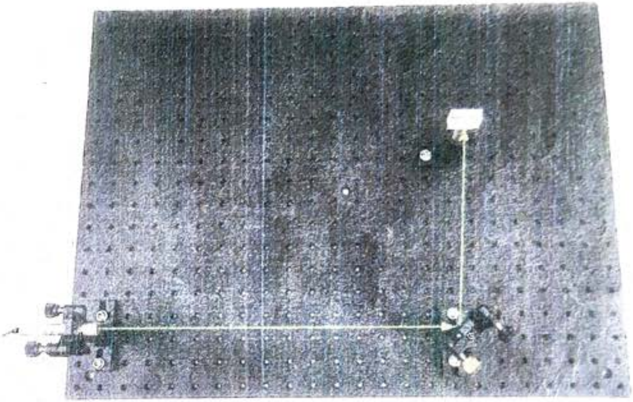


Figure 4 Laser Setup

4.3.2. Mirrors and Beamsplitters

1. Adjust the laser by using the adjustment screws of the kinematic mount to make sure it's as horizontal as possible. Move the height alignment tool from the laser to the end of the breadboard while observing the laser spot's position on the alignment tool. If you haven't done so already, adjust the height of the cross-hair to the middle of the laser spot. This is the reference height for all of the following optical components.

2. Bolt the base of the mounted mirror at the other end of the board so that the laser is reflected by it at a 90° angle. Ideally, you should align the laser beam with the rows of holes in the breadboard, as shown in Figure 4. Moving along the beam path with a screen helps to achieve the 90° reflection angle. Adjust the height of the mount so that the beam hits the center of the mirror and also runs parallel to the surface of the breadboard as much as possible (again, using the height alignment tool).

3. Insert one of the beamsplitters between the laser and the first mirror (labeled as path 1 in Figure 5, below), so that the beam is divided into two perpendicular partial beams.

4. The beam which forms path 2 should be reflected by the second mirror so that the reflected beam runs parallel to the beam in path 1, as shown in Figure 5 below. Ensure that the distances are about the same in both paths.

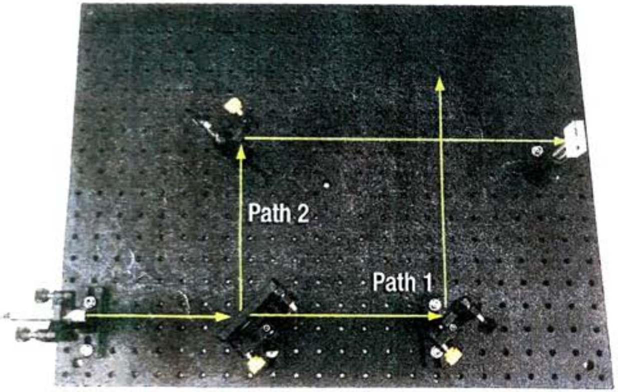


Figure 5 Mirror and Beamsplitter Setup

5. Once again, ensure that the beam runs parallel to the row of holes and adjust the heights of the components.

6. Insert the second beamsplitter at the intersection of the two partial beams in the setup, as shown in Figure 6. Fix it to the breadboard with the CF125 clamp. Make sure that the reflected laser light also has the correct beam height.

4.3.3. Screens and Alignment

7. Set up one of the EDU-VS1(/M) observation screens relatively close behind the beamsplitter (labeled as screen 1 in Figure 6, below) and the other at a distance of about 2 - 3 meters (or ideally an even greater distance). The goal is to overlap and co-propagate both partial beams so that they can interfere with one another.

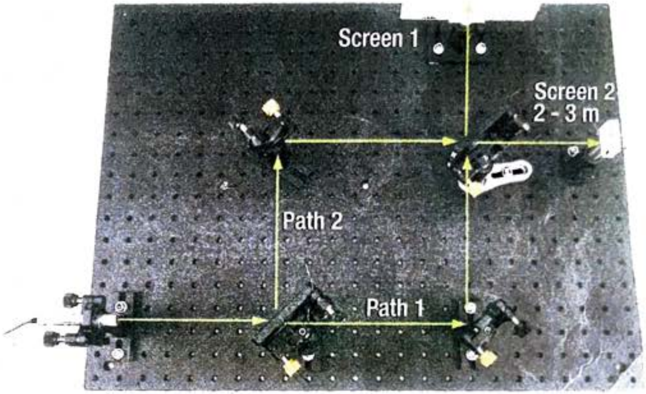


Figure 6 Screens and Alignment

8. Initially, you will probably see two laser spots on the screens. Position the spots on top of one another with the aid of the fine adjustment screws on the mirror and beamsplitter mounts.
   Note: When you adjust the screws on the mirrors, the laser spot will move on both screens in opposite directions (e.g., one spot will move to the right and the other will move to the left). Adjusting the screws on the second beamsplitter will result in movement in the same direction on both screens.

9. Make sure that the two beams overlap well on the beamsplitter. It is not enough to have overlapping spots on the screens! If the beams do not overlap sufficiently on the beamsplitter, change the mirror position accordingly. An interference pattern will only appear when the beams overlap well on the beamsplitter and the screens.

10. There are three possible ways to proceed in adjusting the interferometer. There is no ideal way to do it—please choose your favorite method:

   a. Position the spots according to step 8 such that they overlap. Next, expand the beam to obtain the interference ring pattern by installing the LB1901 lens between the laser and the first beamsplitter. If the interference pattern does not show, slowly tilt and rotate one of the mirrors. If the interference pattern still doesn't show, the previous adjustment steps need to be repeated.

   b. Position the spots according to step 8 until you see a flickering in the laser spots. Next, expand the beam to obtain the interference ring pattern by installing the lens between the laser and the first beamsplitter. If the interference pattern does not show, slowly tilt and rotate one of the mirrors. If the interference pattern still doesn't show, the previous adjustment steps need to be repeated.

   c. Apply a so-called "beam walk". This iterative method is a general procedure applied to align optical beams in which two kinematic elements are used to align the laser to two targets. The two kinematic elements are the first beam splitter and a mirror of your choice. The two targets are the laser spots on the second beam splitter and on one of the screens. Apply the following steps:

      i. Adjust the first beam splitter until the two spots on the second beam splitter overlap as well as possible.

      ii. Adjust the mirror until the two spots on one of the screens overlap as well as possible.

   These two steps need to be repeated until the two beams spots overlap on both the beamsplitter and the screens. Then, install the lens between the laser and the first beamsplitter.

11. Once you have obtained an interference pattern (see Figure 12, below), place a polarizer in each path. With parallel polarization planes, interference is observed, but with perpendicular planes, it disappears (see Chapter 5). The third polarizer ("eraser" with 45° orientation) can now be placed directly in front of one of the screens.

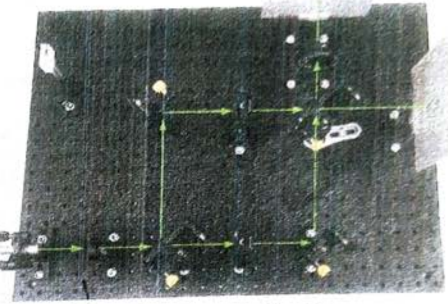


Figure 7 Interferometer Final Setup

4.4. Additional Notes

4.4.1. Complementarity of the Patterns and Phase Shifts

The two output arms of the Mach-Zehnder interferometer show interference patterns that are complementary. This means that if the pattern on one screen shows a dark spot then the other screen shows a bright spot in the same place (and vice versa). The reason is found in the phase shifts at the beam splitters, which we will discuss in the following section.

First we have to examine the beamsplitters themselves: They consist of a glass substrate and a reflective coating on top of one side. Depending on which side of the beamsplitter the laser reflects from, there is either a phase shift of angle φ or not. When light is reflected from the back side (i.e., when it enters the glass first), then no phase shift occurs.

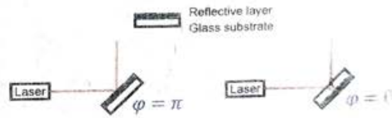


Figure 8 Phase Shifts at a Plate Beamsplitter

Now we can investigate the phase difference on one screen between the two interferometer paths:

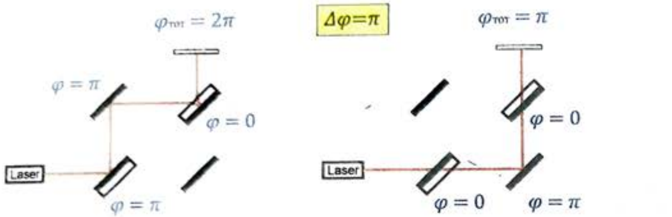


Figure 9 Phase Difference at One Screen

Similarly, we obtain the phase difference on the other screen:

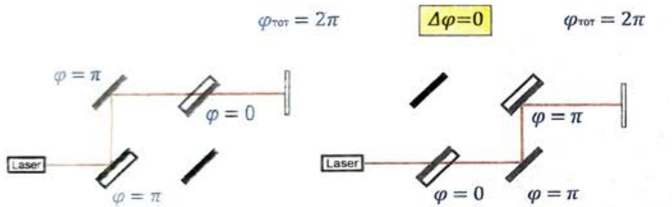


Figure 10 Phase Difference at Other Screen

Therefore, the phase difference between the two screens is always π (180°).

Note: In this discussion, we reglect the phase shift caused by the glass itself (due to the different speed of light in the medium). Here, we only discuss the phase shifts due to the reflections. The phase shift due to the medium introduces another shift of the total phase but does not change the fact that the patterns on the screens are complementary.

Note: You do not have to take care of the orientation of the plate beam splitters when you assemble the setup! It does not matter in which orientation they are placed in the mount (the relative phase shift stays the same).

4.4.2. Ring Pattern

As stated above, the most distinct interference pattern is obtained when both arms of the interferometer are of equal length. In the case where one arm is much longer than the other, an interference pattern can be observed, but it is much smaller than with an optimal adjustment. Here, we discuss briefly why that is the case and why we see a circular pattern.

When the interferometer arms are not of equal length (which is always the case since it's practically impossible to adjust the interferometer with nanometer precision) then there exist two (virtual) light sources as seen by the screen which correspond to the different light paths through the interferometer. If the path is stretched out in one dimension, one source is behind the other due to the different lengths of the interferometer arms.

As with all interference patterns (such as, e.g., for the double slit) one can now determine the difference in the paths length between the path from light source A to point X and from light source B to point X which then translates to, e.g., constructive or destructive interference, see Figure 11.

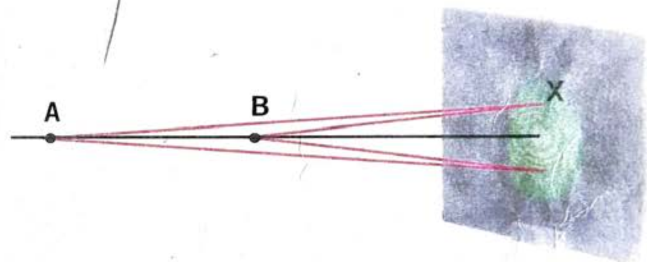


Figure 11 Explanation of a Circular Interference Pattern

If the arms of the interferometer have very different lengths, the two virtual light sources are far apart. In this case, a small position change on the screen corresponds to a large change in the path length difference, which again translates into a smaller spacing between the fringes. This explains why the interference pattern gets smaller when the interferometer arms have very different lengths.

This line of argument is the same for all points on the screen. Since the lens diverges the beam symmetrically around the optical axis, the interference pattern needs to be symmetric, i.e., concentric, as well.

Chapter 5 Experiment

First, it should be pointed out once again that this experiment represents an analogy experiment to the true single-photon "quantum eraser", as it can also be explained in purely classical terms. In the original single-photon experiment, classical physics ultimately fails. In spite of this, the experiment can be described with quantum mechanics principles and terminology.

The quantum eraser serves to illustrate several basic quantum mechanics principles and "mysteries", such as complementarity or the quantum mechanics measuring process in conjunction with interference phenomena.

The two possible paths in the interferometer represent two possibilities for one photon to move. The two polarizers are used to mark the paths, which makes them distinguishable.

5.1. Experiment 1: Path Information in Quantum Physics

Place a polarizer in each arm of the interferometer and adjust the polarization of both to the same orientation.

You should still see interference rings on both screens. Now imagine that only a single photon passes through the setup at a time. One often uses the expression that the photon interferes "with itself". From a quantum mechanics point of view, this means that the state of the photon is a superposition of the two states: "photon in path 1" and "photon in path 2". The probability of each of the two possibilities is 50%. The intensity pattern, which one can observe on the screen after many individual photons have passed through the setup, meaning the probability distribution of these photons, emerges as an interference pattern (see Figure 12). We do not know which path the photon took, as both paths are indistinguishable.

Now, turn one of the polarizers by 90°. The different paths in the interferometer are now "marked" by polarization, and so we obtain information regarding the path that the photon took. This results in the disappearance of the interference pattern, as the two paths are now distinguishable. A smooth intensity distribution appears on the screen without an interference pattern (see Figure 13).

If the interference pattern does not fully vanish when the polarizers are set to 0° and 90°, it is most likely caused by non-perpendicular polarizers. You may need to make sure again that the film polarizers have the correct orientation in their mount (c.f. chapter 4.2 component assembly).

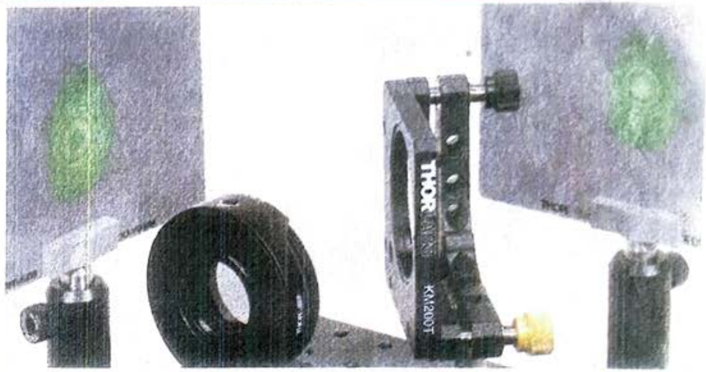


Figure 12 Interference Patterns

Figure 13 Disappearance of the Interference Pattern

rick question:

Above, we've argued that the presence of a 0° polarizer in one arm and a 90° polarizer in the other arm of the interferometer results in a defined path and no interference pattern. We argued that the photon will have either 0° or 90° polarization on the screen/detector and that we could thereby tell which way it went. Does the same line of argument work when a 0° and an 80° polarizer are used?

Answer:

One might be inclined to say "yes" since one might make the mistake of thinking that a photon that has an 80° polarization at the screen must follow the path with the 80° polarizer. However, there is a certain probability that a photon polarized at 0° will be absorbed on the screen with 80° polarization, even though the probability is small. Therefore, the path information is undefined. In other words: the two possible paths (or possible states) superimpose, and we find a low contrast interference pattern.

5.2. Experiment 2: Quantum Eraser

In this experiment, the two polarizers in the setup should first be turned 90° in relation to one another, as described above, so that no interference is observable due to the path information. Then, the third polarizer, the "eraser", is installed between the last beamsplitter and a screen. The eraser is oriented 45° from the other two polarizers. What can be observed on the screen?

As one can see in Figure 14, an interference pattern appears again. Figure 14 shows the screen with the eraser in front of it on the left hand side and the screen without eraser on the right hand side. Therefore, an interference pattern is observable on the left screen whereas no pattern is observable on the right screen.

These observations can be explained as follows: the eraser restores the interference pattern again, as the path information of the photons is now no longer present. All photons, which hit the screen, have a 45° polarization. The photons, which reach the other screen without the "eraser", still carry this path information – one can determine whether they passed through path 1 (0° polarization) or path 2 (90° polarization). Therefore, no interference pattern is observable on the right screen.

Figure 14 Right Screen: No Interference Pattern. Left Screen: Interference Pattern Behind the Eraser

5.3. Experiment 3: Thought Experiment

The physicist John Wheeler came up with the following thought experiment: Imagine that the second beamsplitter is inserted into the setup after the photon (according to classical thinking) must have already "chosen" one of the two possible paths in the interferometer. What result is expected—interference or not?

First of all, we sketch the interferometer, with and without the second beamsplitter:

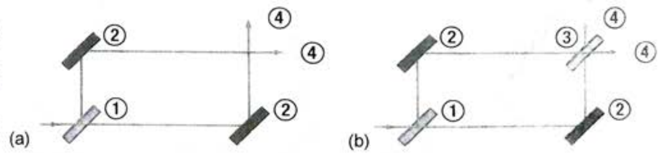


Figure 15 (a) Sketch of the Setup without the Second Beamsplitter, (b) Setup with Second Beamsplitter, (1) First Beamsplitter, (2) Mirror, (3) Second Beamsplitter, (4) Screens.

When a photon is sent into the setup depicted in Figure 15(a), the path information is defined. As a result, no interference pattern is visible. As we've discussed above, the setup in Figure 15(b) leads to an interference pattern because the path is undefined. Wheeler now asks the following question: what if we send the photon into the setup depicted in Figure 15(a) and insert the second beamsplitter *after* the photon has passed the first beamsplitter—do we see an interference pattern? Do we have a defined path or not?

First, we note that "after the photon has passed the first beamsplitter" is a formulation we can only use in classical physics! Unless we measure the position of the photon, we can't make statements about it. This sentence is supposed to say 'we wait a certain time until the photon is (classically speaking) behind the first beamsplitter". If we thought in terms of classical physics, we would have to assume that the photon chose one of the paths at the first beamsplitter. Therefore, the insertion of the second beamsplitter would not have any impact, and we would not see an interference pattern.

Quantum physics offers a surprise, though; when the second beamsplitter is inserted, the interference pattern is observable again! The conclusion is that a quantum physical system does not have to decide on particle or wave properties until an observer performs a measurement. This is true even when we decide what property we want to measure after the experiment has already started. For that reason, experiments such as the one Wheeler proposed are called "delayed-choice-experiments".

This experiment has now actually been performed and this explanation was confirmed (see, for example *Hellmuth, Walther, Zajonc, Schleich, Phys. Rev. A* **35**, *2532(1987)*). It shows the extremely non-intuitive nature of quantum mechanics and the quantum mechanical measurement process.

Chapter 6 Teaching Tips

- **Students can Set Up and Adjust the Interferometer.**

  The quantum eraser is based on a Mach-Zehnder interferometer that can be set up and adjusted by the students themselves. Depending upon experiment experience, however, the high degree of variability is problematic here – ultimately, the alignment of any mirror and any beamsplitter can be adjusted. In order to simplify setup and adjustment, gold screw heads are attached to several adjuster knobs. Once the interferometer has been successfully adjusted, one can disassemble it and give it to the students to set up again with the limitation that only the gold screws should be turned. In this manner, adjustment is simplified and the number of experimental variables minimized.

- **Classical vs. Quantum Interpretation**

  The central misunderstanding, which occurs in any path information experiment, is due to the insistence on the classical idea that a photon must decide on a path through the interferometer. It is important to emphasize that this is only the case if the respective measurement is carried out – in this context, the importance of the measurement process in quantum physics becomes clear.

- **Superposition of Quantum States**

  In order to make it easier for the students to transition to the concept of states, it is recommended to discuss the concept of states based on Schrödinger's cat. The system consists of a box, a cat, and a poison, which is released upon the decay of a radioactive atom (a random process). The system has two states as long as the box is closed: the poison has not yet been released and the cat is alive (state 1) or the poison has already been released and the cat is dead (state 2). The central aspect of this thought experiment is that all states of the system exists simultaneously and superpose one another. However, as soon as the box is opened, the system must transition to *one* state.

  Schrödinger's cat therefore represents a good introduction to the concept of states. In addition, this thought experiment also helps one understand the quantum eraser because two states exist here as well, namely the two possible paths of the photon through the interferometer. If no explicit measurement is performed to determine in which arm of the interferometer the photon is located (if the "box" is not opened), the states are superposed and create the familiar interference pattern.