EDU-BT1
EDU-BT1/M
Bomb Tester

User Guide

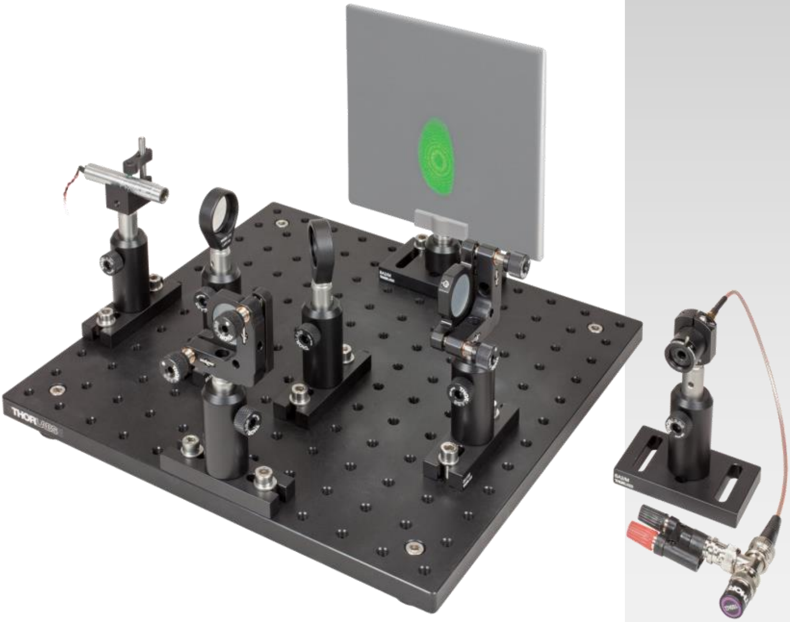
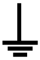


Table of Contents

Scan Here For
More Information

Chapter 1 Warning Symbol Definitions

Below is a list of warning symbols you may encounter in this manual or on your device.

Symbol	Description
	Direct Current
	Alternating Current
	Both Direct and Alternating Current
	Earth Ground Terminal
	Protective Conductor Terminal
	Frame or Chassis Terminal
	Equipotentiality
	On (Supply)
	Off (Supply)
	In Position of a Bi-Stable Push Control
	Out Position of a Bi-Stable Push Control
	Caution: Risk of Electric Shock
	Caution: Hot Surface
	Caution: Risk of Danger
	Warning: Laser Radiation

Chapter 2 Safety

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.

Chapter 3 Brief Description and Basic Ideas

Can one measure the presence of an object without interacting with the object? In other words, can one see an object that may not be exposed to a single photon? In the macroscopic world, this seems absurd. But in quantum physics, it is actually possible according to the principle of “interaction-free quantum measurement”. The two physicists, Elitzur and Vaidman, published a thought experiment on this in 1993[1], the “Bomb Tester”.

At the beginning of the thought experiment, there are a certain number of bombs, which are designed so that they explode as soon as they are hit by even a single photon. The problem is that some of them are defective and do not explode, meaning that they are duds. Externally, the duds cannot be differentiated from the functioning bombs. How does one determine which bombs work and which do not? If a photon is directed at them, all functional bombs will logically explode. Is there another possibility?

Quantum mechanics allows for such a test: an interaction-free quantum measurement that will allow the user to sort out at least some of the good bombs. In a classroom setting, an analogy experiment can be used to highlight the idea of interaction-free quantum measurements through the use of a Michelson interferometer. Here it is important to understand what a quantum mechanics “which-path” system is and how a measurement of it can destroy interference.

The remainder of this manual will give a components list and instructions for setting up an interferometer. After that, there will be a brief introduction to quantum mechanics that contrasts the relevant predictions of quantum mechanics to its classical physics counterpart. Once the background information is known, interference-free quantum measurements are then introduced. Finally, we conclude with an analogy experiment that can be performed by students in the classroom.

[1] A. Elitzur, L.Vaidman: *Quantum mechanical interaction-free measurements*, Foundations of Physics **23**, 1993, p. 987-997

Chapter 4 Setup and Adjustment of the Michelson Interferometer

4.1. Overview of the Individual Components

In cases where metric and imperial kits contain parts with different item numbers, metric part numbers and measurements are indicated by parentheses unless otherwise noted.

 1 x **CPS532-C2** 532 nm Laser Diode Module	 1 x **DS5** 5 VDC Regulated Power Supply	 1 x **CPSA** USB to Phono Cable for CPS Lasers
 1 x **VC1(/M)** Small V-Clamp with PM3(/M) Clamping Arm	 1 x **LB1901** Ø1″ N-BK7 Bi-Convex Lens, f = 75.0 mm	 1 x **SM1RR** SM1-Threaded Retaining Ring
 1 x **EBS1** Economy Beamsplitter, Ø1″	 2 x **ME1-G01** Ø1″ Protected Aluminum Mirror, 3.2 mm Thick	 2 x **KM100** Kinematic Mount for Ø1″ Optics

 2 x **LMR1(/M)** Lens Mount for Ø1″ Optics	 1 x **SM05D5** Internally SM05-Threaded Lever Actuated Iris Diaphragm	 1 x **SM05M10** 1″ Long, SM05-Threaded Lens Tube
 1 x **SM05PD1A** Silicon Photodiode, 350 – 1100 nm, Cathode Grounded	 1 x **SM05RC(/M)** Ø1/2″ Slim Slip Ring for SM05 Lens Tubes, 8-32 (M4) Tapped Hole	 1 x **CA2812** 12″ Long SMA Coaxial Cable, SMA Male to BNC Male
 1 x **T3285** BNC Adapter – T Adapter (F-M-F)	 1 x **FT104** 100 kΩ Fixed Stub-Style BNC Terminator	 1 x **T1452** BNC Female to Binding Post
 1 x **EDU-VS1(/M)** Viewing Screen	 6 x **TR2 (TR50/M)** Ø1/2″ (Ø12.7 mm) Post, 2″ (50 mm) Long	 1 x **TR075 (TR20/M)** Ø1/2″ (Ø12.7 mm) Post, 3/4″ (20 mm) Long

 1 x **PH1 (PH20/M)** Ø1/2″ (Ø12.7 mm) Post Holder, 1″ (20 mm) Long	 6 x **PH2 (PH50/M)** Ø1/2″ (Ø12.7 mm) Post Holder, 2″ (50 mm) Long	 5 x **BA1(/M)** Post Holder Mounting Base, 1″ x 3″ x 3/8″ (25 mm x 58 mm x 10 mm)
 2 x **BA2(/M)** Post Holder Mounting Base, 2″ x 3″ x 3/8″ (50 mm x 75 mm x 10 mm)	 1 x **MB12 (MB3030/M)** Aluminum Breadboard, 12″ x 12″ x 1/2″ (300 mm x 300 mm x 12.7 mm), 1/4″-20 (M6) Taps	 1 x **RDF1** Rubber Dampening Feet, Set of 4

Imperial Kit Hardware:

 1 x **BD-3/16L** 1/4″-20 Ball Driver	4 x 1/4″-20 Socket Head Screw, 3/4″ Long
	12 x 1/4″-20 Socket Head Screw, 5/8″ Long
	6 x 1/4″-20 Socket Head Screw, 1/2″ Long
	1 x 1/4″-20 Cap Screw, 3/8" Long
	12 x M6 Washer
5/64″, 7/64″, and 9/64″ Hex Keys	4 x 1/4″-20 Nut

Metric Kit Hardware:

 1 x **BD-5ML** M6 Ball Driver	4 x M6 Cap Screw, 20 mm Long
	12 x M6 Cap Screw, 16 mm Long
	6 x M6 Cap Screw, 12 mm Long
	1 x M6 Cap Screw, 10 mm Long
	12 x M6 Washer
2 mm, 2.5mm, and 3 mm Hex Keys	4 x M6 Nut

4.2. Assembly of the Components

First, screw the rubber feet onto the breadboard.

Then, assemble the different components of the setup as follows[2]:

Screen

Components:
Screen
3/4″ (20 mm) Long Post
1″ (20 mm) Long Post Holder
BA2(/M) Base

Lens and Beamsplitter

Components:
Lens or Beamsplitter
LMR1(/M) Lens Mount
2″ (50 mm) Long Post
2″ (50 mm) Long Post Holder
BA1(/M) Base

[2] In cases where metric and imperial kits contain parts with different item numbers, metric part numbers and measurements are indicated by parentheses unless otherwise noted.

Mirrors

Components:
Mirror
KM100 Kinematic Mount
2″ (50 mm) Long Post
2″ (50 mm) Long Post Holder
BA1(/M) Base

Laser

Components:
Laser
Small V-Clamp
2″ (50 mm) Long Post
2″ (50 mm) Long Post Holder
BA1(/M) Base

Mounting the KM100 on a Post

Instead of a threaded hole for mounting, the KM100 has a counterbored hole. To post mount these parts, first remove the setscrew from the post that you are using. Insert an 8-32 (M4) cap screw through the counterbored hole in the universal mount, and tighten it into the post on the other side of the hole.

Photodetector

Components:

Photodetector (in Lens Tube)	Lens Tube
12″ BNC to SMA Cable	Lens Tube Slip Ring
BNC T-Adapter	Iris Diaphragm
Stub-Style BNC Terminator	2″ (50 mm) Long Post
Binding Post	2″ (50 mm) Long Post Holder
	BA2(/M) Base

Photodetector Assembly

Connect a PH2 (PH50/M) 2″ (50 mm) long post holder to a BA2(/M) base. Screw a TR2 (TR50/M) 2″ long (50 mm) post into the SM05RC(/M) lens tube slip ring and insert it into the post holder. Next, screw the SM05PD1A photodiode into one end of the SM05M10 lens tube and the SM05D5 iris onto the other. Insert this assembly into the slip ring and attach the CA2812 SMA to BNC adapter cable. Connect the cable and the FT104 BNC terminator to either end of the crossbar at the top of the T3285 BNC T-adapter. Finally, attach the T1452 BNC to binding post adapter to the base of the T-adapter.

4.3. Setup and Adjustment

In the Michelson interferometer, a laser beam is split by a 50:50 beamsplitter; the split beams are then reflected back by mirrors and recombined at the beamsplitter. A screen or detector at the output of the interferometer shows an interference pattern if the two paths are indistinguishable. A lens is used to expand or diverge the beam in order to obtain an interference pattern consisting of light and dark rings (constructive or destructive interference, respectively). The complete setup is shown in Figure 1. Instructions are given below.

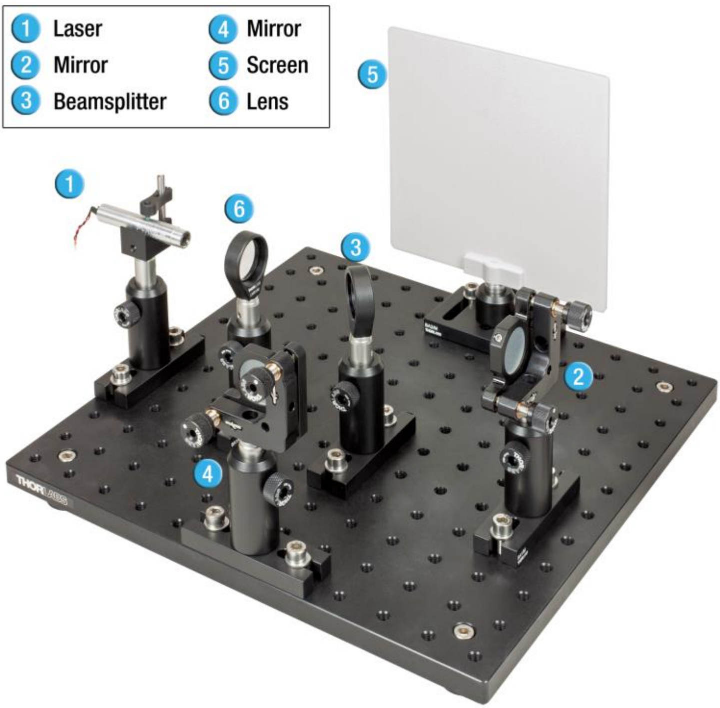


Figure 1 Setup of the Interferometer

1. First, position the laser (1) in the mount at the edge of the breadboard and secure it with the appropriate cap screws. Align the beam as closely as possible with the rows of holes in the breadboard.

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.

2. Next, place the first mirror (2) on the optical axis of the laser beam and orient the mirror such that the beam reflects approximately back into the laser (at these low power levels, this will not damage the laser).

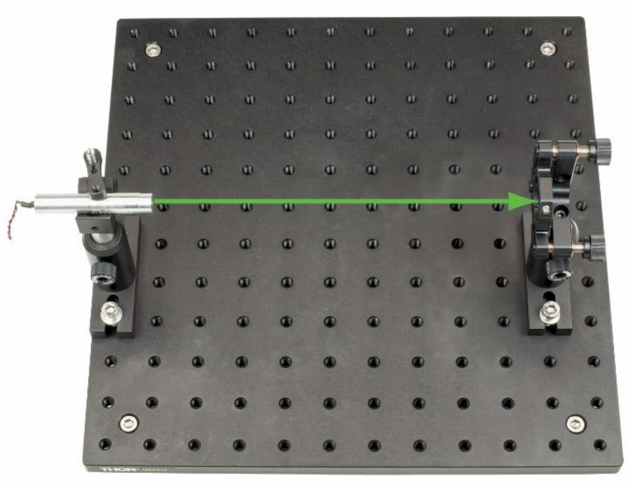


Figure 2 Placing the Laser and the First Mirror

3. Install the beam splitter (3) and ensure that the beam is split at a 90° angle.

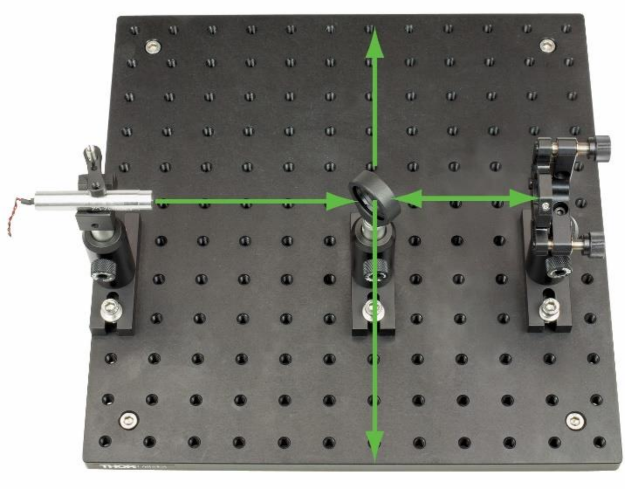


Figure 3 Placing the Beam Splitter

4. Next, install the second mirror (4) and ensure that the beam reflected by this is superimposed over the first beam at the beamsplitter. This can be accomplished by means of the fine adjustment screws. In particular, one should ensure that the distance between the beamsplitter and the mirrors is the same along both interferometer arms.

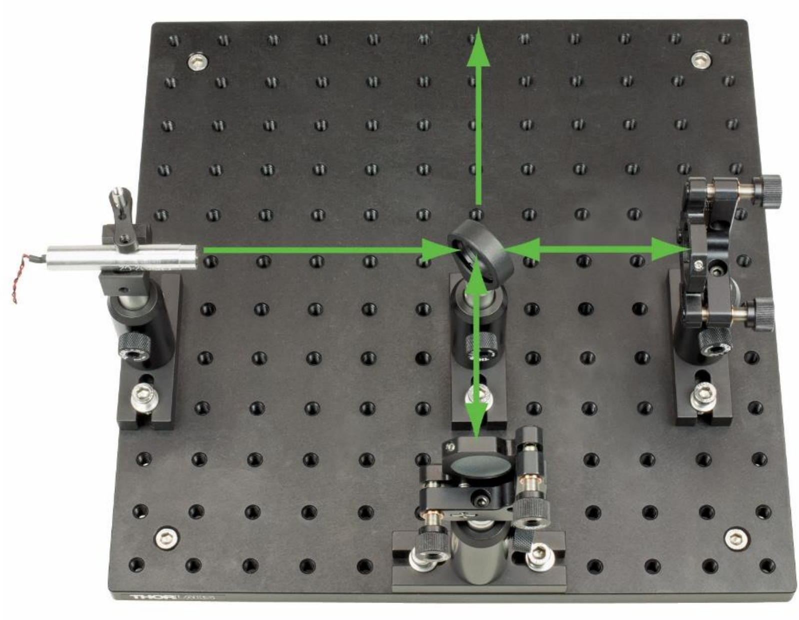


Figure 4 Placement of the Second Mirror

5. Place the screen (5) at the output of the interferometer. You should now see the two partial beams as points, which more or less overlap. Ideally, you should already see a slight flickering there – this indicates interference.

6. Finally, place the lens (6) between the laser and the beamsplitter. You may already see interference rings or stripes. If not, turn the screws on the (second) adjustment mirror and try to create interference. If you are still unsuccessful, check that the partial beams really overlap on the surface of the beamsplitter (it is not sufficient if they only do so on the screen). Tip: You can use a hex key in the adjuster screws for smoother alignment.

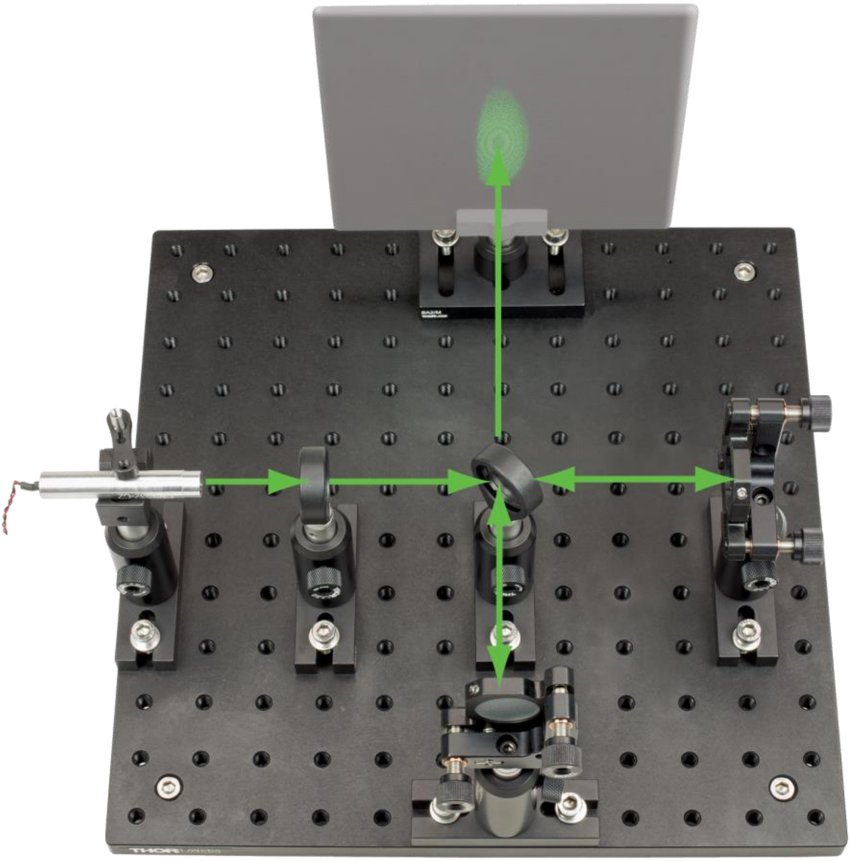


Figure 5 Placement of the Lens and Screen

Additional note:

As stated earlier in this section, 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 both 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 (e.g., for the double slit) one can now determine the difference in the path lengths between the path from light source A to point X and from light source B to point X, which then translates to constructive or destructive interference (see Figure 6).

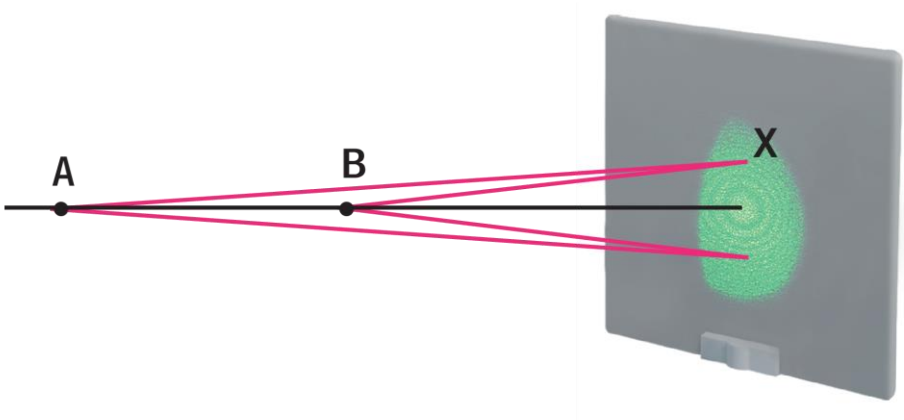


Figure 6 Explanation of a Circular Interference Pattern

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 Instructions and Exercises

5.1. Which-Path Experiments: Where Classical Physics Fails

First, we should contemplate quantum mechanical relationships by proceeding mentally from classical physics to quantum mechanics.

Exercise:
We first consider what will happen if we send, for example, 4 photons from the laser into the setup. A diagram of the interferometer is shown in Figure 7. We can represent each of the photons with a 1-cent coin and track their paths through the interferometer. What happens?

1. Decision: In classical thinking, each photon can only take path one or path two. We know that the probability of each is 50%. We will therefore assume that two photons take path 1 and two photons take path 2 and place the respective number of coins on the two interferometer arms. Each of the photons is then reflected by a mirror and moves back to the beamsplitter. All four coins thus return to the splitter.
2. Decision: At the beamsplitter, there is once again a which-path decision for each photon. The two photons from path 1 and the two photons from path 2 can be transmitted again or reflected. We once again have a 50:50 probability and, therefore, allow each photon or coin to take one of the possible paths.

   So, in the end, two coins end up at the screen and two back in the laser. Someone who has not looked at the coins while they were in the setup cannot say which coin took which path. On a detector, this would result in an interference pattern. This simple, intuitive demonstration is clear from a classical point of view.

Discovery of misconceptions: Students might assume that the various photons interfere with one another here, which naturally is NOT the case.

Let us now do the same with only one single photon or, for the purposes of our demonstration, with a single coin. What happens at the beamsplitter now?

If the photon/coin cannot be divided, how can it simultaneously be in path 1 and path 2, as we are taught by quantum mechanics? This example demonstrates the breakdown of classical physics, as classically the photon/coin cannot be in path 1 and 2 simultaneously. Instead, we must turn to quantum mechanics. In quantum mechanics, we call each potential path of the photon a possible state, which is described by the so-called wave function, Ψ (Psi); a mathematical description for this state.

We cannot think of the photon as a classic object like a coin. This perception falls short and does not explain the observed phenomenon. With the wave functions, we now describe two states of a single photon; the photon exists simultaneously in each of the two states (as long as one does not determine where it is located). These can interfere with one another. The photon is therefore not localized at a fixed point but is located on both paths simultaneously. When we consider what happens at the beamsplitter, we realize that the photon never actually "decides" which path it will take. It is simply present on both paths with its wave functions.

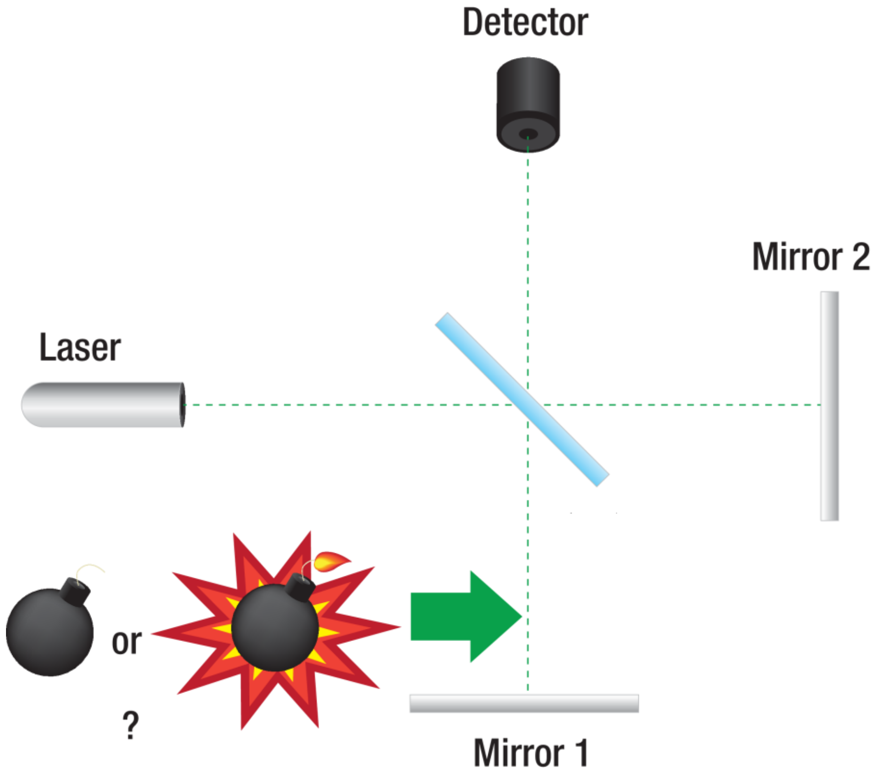


Figure 7 Sketch of the Michelson Interferometer – Placing the Bomb

Only when one “looks” or marks the photon due to a disruption in one of the paths (such as with a bomb as described below) does the respective wave function collapse and only one path is allowed. In this instance, interference is no longer possible (this corresponds to blocking the beam in one arm of the interferometer).

Conclusion: If the paths are indistinguishable in the interferometer, the two potential paths (wave functions) of a photon interfere with each other; an interference pattern is visible on the screen.

If the paths can be distinguished, meaning that path information exists, the wave function collapses into a single function corresponding to the only remaining possible path once the photon is detected. The other wave function disappears, and interference can no longer take place.

5.2. Experiment Regarding Interaction-Free Quantum Measurements: Testing the Bombs in the Michelson Interferometer

In the following, we will use expressions such as "the photon takes path 1". As we just established, this expression is not completely correct, as the photon does not really decide and has the same probability of being present on both paths up until the measurement process. Consider the case where a functional bomb is placed in path 1 of the interferometer. If the bomb explodes, instead of saying "the photon took path 1", we should say "the photon was detected in path 1." Up to the point in time when the photon interacted with the bomb, there was an equal probability of the photon existing in both arms of the interferometer. Only when the photon is absorbed by the bomb does the wavefunction collapse into a single state. In order to not unnecessarily overcomplicate the explanation below, however, we will use the more intuitive language for referring to the photon's location.

5.2.1. What is an interaction-free quantum measurement?

Use a common Michelson interferometer, as portrayed in Figure 7. The beamsplitter transmits 50% of the photons and reflects 50%. The interferometer should be set so that destructive interference exists at the detector.

The bomb is now placed on the lower arm (path 1) of the interferometer, between mirror 1 and the beamsplitter. If the bomb is live, it interacts with photons and detonates. On the other hand, if the bomb is defective, no interaction occurs and the photons pass through the defective bomb without being "detected".

Now, a photon is sent into the setup.

Let us initially assume that the bomb is functional and detonates upon meeting a photon. We now consider the following possibilities, which can occur after a photon leaves the laser:

A) The photon is transmitted at the beamsplitter and takes the path of the upper interferometer arm (path 2), where no bomb is located. It is then reflected at mirror 2 and, either passes through the beam splitter back to the laser cavity or is reflected by the beamsplitter towards the detector.

The detector detects a photon in 50% of the cases; it remains dark in 50%.

(A.1) In the cases in which the detector remains dark, meaning the photon passes back into the laser, we cannot make any statement regarding whether there was a live bomb in the setup or not.

(A.2) In the case where the photon is detected by the detector, we know that the interference pattern has been destroyed (if the interference pattern created by the two states of the photon's wavefunction was intact, the photon would not reach the active area of the detector). The photon's wave function has collapsed into a single state and something must be located in the interferometer arm. This means that we have detected the live bomb without detonating it.

B) The photon takes the lower path (path 1) and meets the bomb – the photon is absorbed by it and the bomb detonates.

Let us now assume that a dud is located on the lower arm. The situation is as follows:

C) As the bomb does not interact, the set interference (destructive interference at the detector) remains intact in the interferometer and the detector always remains dark.

Now, let us consider our measurement situation for evaluation: either a live or defective bomb (unknown at this time) is placed in the setup. After sending in a single photon, there are three possible outcomes:

1. After sending the first photon, we obtain darkness on the detector: We cannot make any statement (case A.1 or case C) and must send an additional photon into the setup.
2. We obtain an explosion and the detector remains dark, as the photon was absorbed by the bomb: clearly, case B.
3. We measure a photon at the detector: We know with certainty that a functional bomb is in the setup (case A.2).

In the event of result 1, additional photons must be sent into the interferometer to prove that the bomb is a dud. Each additional photon may produce results 1 through 3. If we always obtain darkness on the detector after sending a high number of photons, we know that we have a dud in the setup and can reject it (case C).

In conclusion, it is found that a live bomb can be proven in 25% of cases without detonating it. In 50% of cases, a live bomb explodes and in 25% no statement can be made, as the photon propagates into the laser again.

Ultimately, this also means that we can determine the presence of a functional bomb without the necessity of an interaction between a photon and the bomb! Just the detection of a photon implies that the wavefunction has collapsed into a single state due to the presence of the bomb, settling this debate.

5.2.2. Analogy Experiment Regarding Interaction-Free Quantum Measurements for the Classroom

Today, the experiment above can be easily performed by using single-photon sources and detectors and the theory behind the thought experiment can be confirmed. Unfortunately, such setups are too complicated and too expensive for the classroom. However, one can perform analogy experiments with "many photons", meaning continuous laser light, in order to demonstrate the subject matter. The transition to a single photon must then be made mentally.

For the analogy experiment, one also uses a Michelson interferometer. There is no single-photon source this time, but rather a laser. The detector is not a single-photon detector, but rather a photodiode detector, which simply measures light intensities. Ultimately, single-photons are not measured, but rather the probabilities of the possible paths/states (integrated over many photons) which the photons can take.

Figure 8 Setup for Measurements

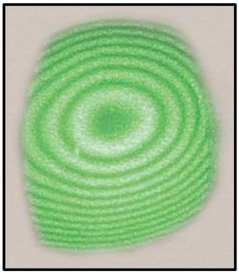
You can connect the photodetector to any multimeter. The measurable voltage values lie in the mV-range.

In the following steps, reference is made to the example results in Table 1. The results came from three series of measurements, which were performed in daylight and at different distances between the detector and the beamsplitter (distance increasing from measurement 1 to 3), which can be seen immediately from the overall intensity.

If you reduce the opening of the iris diaphragm, sufficient daylight is blocked so the experiment can be performed reasonably. Room darkening is therefore not absolutely necessary.

Step 1

Measure the total intensity (represented as photodiode voltage) of the beams in both arms of the interferometer. Misalign the interferometer initially by turning the adjustment screws of one mirror. Turn until the interference/ring pattern disappears. Now, measure the voltage on the detector. This voltage only represents half of the overall intensity (50% of the total light from each arm of the interferometer will be directed back towards the laser), so you must double this value (see Table 1, Column 2).



Now, adjust the interference pattern by turning the adjustment screws on the mirrors so that a minimum (meaning darkness) exists in the center[3].

The photodiode should now be placed in the center of the interference pattern and the iris diaphragm closed as much as possible, so that only a small opening can still be seen[4]. The voltage on the photodiode will not reach zero because ambient light can enter and, realistically, a perfect minimum can usually never be achieved. You can simply accept the value as an offset (see example results in Table 1, Column 3).

Step 2

We now simulate the possible cases of the bomb experiment with measurements:

1. We have a dud in the setup. As we do not have any objects in the macroscopic world that do not interact with light, we will not place anything at all in the setup for this case (or a the "dummy" dud bomb provided in Chapter 6 can be used to visually illustrate the presence of the dud). The photodiode remains at the same low value, the destructive interference is maintained. This means that photons (except for noise and any ambient room light) still do not hit the detector. We obtain a low offset value, as we probably do not perfectly hit the minimum.

2. We have a functional bomb in the setup. For this, simply block the light in one arm of the interferometer, e.g. with the print out of the active bomb provided in Chapter 6. The interference is destroyed (distinguishability of the paths). We no longer have a minimum at the center of the detector. The voltage at the photodiode increases[5]. The measured voltage is approximately ¼ of the total voltage (see example results in Table 1, Column 4 or 5[6]). This means that 25% of the emitted photons now hit the detector. These are precisely the photons that reveal the presence of the functioning bomb in the interferometer. If we were able to individually send photons into the setup, we would obtain the same percentage relationship after many emitted single photons.

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[3] If the laser has not yet stabilized, the interference pattern will fluctuate greatly. It should be switched on several minutes before performing the experiment, as it must first warm up to operating temperature and will demonstrate fluctuations until it does.

[4] You can also open the diaphragm further, if you want higher intensity, but you will then obtain more ambient noise in the detector. On the other hand, you can compensate for this by darkening the room.

[5] This is an interesting result: We block half of the light in a manner of speaking, but “it gets brighter.” This aspect can provide inspiration in the classical electrodynamics classroom when the concept of interference appears for the first time.

[6] In general, it does not matter which arm of the interferometer you block. We would really expect the same voltage value in any arm; however, this can never be achieved, because the divergence of the laser always causes small differences. You should therefore either choose a single arm to block when performing this demonstration or discuss the respective sources of errors when comparing the results after the bomb is moved from one arm to the other.

From the examples in Table 1, we see that all measurements result in values of about 23% to 27% instead of the expected 25%. The sources of error, which can be traced back to losses at the beamsplitters and mirrors and measurement inaccuracies when setting up the detector, should be discussed with the students.

Column 1	Column 2	Column 3	Column 4	Column 5
Measurement	$I_{total,laser}$ [mV]	$I_{minimum}$ [mV]	$I_{Arm1,open}$ [mV]	$I_{Arm2,open}$ [mV]
1	50.4 · 2 = 100.8	4.1	22.8	27.6
2	20.5 · 2 = 41.0	1.2	9.3	11.2
3	9.5 · 2 = 19.0	0.9	4.4	5.1

Table 1: Sample results from three measurements. The distance between the detector and the beam splitter was increased before each subsequent trial. While the table lists the voltages measured from the photodetector, these are proportional to the intensitites.

Additional Note:

What happens if constructive interference is set in the center, meaning a maximum in the intensity? Naturally, this should also work the same way, because a path/interferometer arm is also indicated by the bomb in this case. Thus, the quantum physics superposition of the two possible states of the system (namely both paths) collapses and no interference can be observed.

Adjust the interferometer accordingly and measure as above. Now, introduce the bomb into the setup (blockage of a light path). What result do we now expect at the detector?

Before introducing the bomb, we logically obtain a high voltage value at the detector, as we now find an intensity maximum in the center[7].

We now block one of the two paths and once again measure the the voltage from the detector. This value is also 25% of the voltage measured for the total intensity of the laser. This was to be expected: as in Step 2, we have once again destroyed the interference pattern. However, adjusting the interferometer to produce constructive interference in the center of the fringes is not helpful for quantum mechanical testing using single photons. A single photon can reach the detector both in the case of a live bomb in the system and in the case constructive interference, i.e., no bomb or a dud in the setup and no conclusion can be drawn.

[7] No statements should be made here based on the absolute value of the voltage measured in the central maximum of the interference pattern. This information is irrelevant for the experiment. The voltage measured after one arm of the interferometer is blocked should be compared to the total power from the laser as measured in Step 1.

5.3. How Many Active Bombs Can Be Identified in Total?

So far, we have investigated what happens to a photon that is sent into the setup according to theory and what we observe in the analogy experiment. We also discussed the probabilities for observing the system in different states. As a final step, we can ask: how many of the active bombs can be "saved", i.e., how many bombs can we identify as active without detonating them?

For starters, let us consider an example scenario where we have 80 active bombs and a certain number of duds.

We can summarize what we've learned so far. If an active bomb is in the setup and we send in a photon, the bomb will explode in 50% of all cases. In 25% of cases the photon is reflected back in the direction of the light source and in 25% of cases the photon hits the screen, thus revealing the bomb to be active. For our 80 active bombs this means that (neglecting statistical fluctuations):

- 40 bombs explode (50%).
- 20 bombs are proven to be active without detonating them (25%).
- 20 bombs cannot be classified since the photon is neither detected at the screen nor do we see a detonation. These are the cases where the photon is reflected back towards the light source (25%).

Consequently, we have to do another test run with the 20 bombs that were not classified. The result of the second test run will be

- 10 bombs explode (50%).
- 5 bombs are proven to be active without detonating them (25%).
- 5 bombs cannot be classified even in the second run (25%).

We can continue this process of retesting the bombs that cannot be classified until there are no undetonated or proven-active bombs left. Mathematically, this means that we need to re-test a subset of 25% of bombs after each run. For a total number of bombs A, we can summarize the number of saved, active bombs by the following equation:

$$\#\ of\ saved, active\ bombs = \sum_{i=1}^{\infty} A \cdot \left(\frac{1}{4}\right)^{i} = A \cdot \frac{1}{3}$$

Therefore, we can theoretically identify up to one third of all active bombs without detonating them.

Chapter 6 Teaching Tips

- In order to understand the "bomb tester", one should already be familiar with basic concepts of quantum mechanics. Terms such as the interference of quantum mechanical states and the topic of measuring processes in quantum mechanics should ideally have been introduced previously (e.g. Schrödinger's Cat, see below).

- One should always be aware that the statement "the photon takes path 1", etc. is incorrect. The photon does not decide upon a path. In reality, one can only say where it is located once one has performed a measurement (detector, screen, etc.). Nonetheless, it would probably create more confusion if one were to state that the photon could be in "Eigenstate 1", etc. For the sake of clarity, the above-mentioned statement is therefore used.

- In the analogy experiment, only light intensities are measured. Respective results (percentage rates) can therefore be completely explained classically (electrodynamics/optics). However, one can switch to the quantum mechanics photon example for purposes of illustration and interpret the results with the students in this sense. "25% measured light intensity" would therefore mean that a photon has a 25% probability of hitting the detector, or that out of 100 photons sent into the setup, 25 would be registered in the detector.

- In our experience, the Michelson interferometer can be set up and adjusted by the students themselves.

- As illustrated and discussed in Chapter 3, either destructive or constructive interference in the center of the interference pattern can be utilized as an initial basis for measurement. In practice, we have found that the bomb tester is easier to understand if destructive interference is used.

- The central misunderstanding, which occurs when contemplating any which-path experiment, is due to the ingrained 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 measuring process in quantum physics becomes clear.

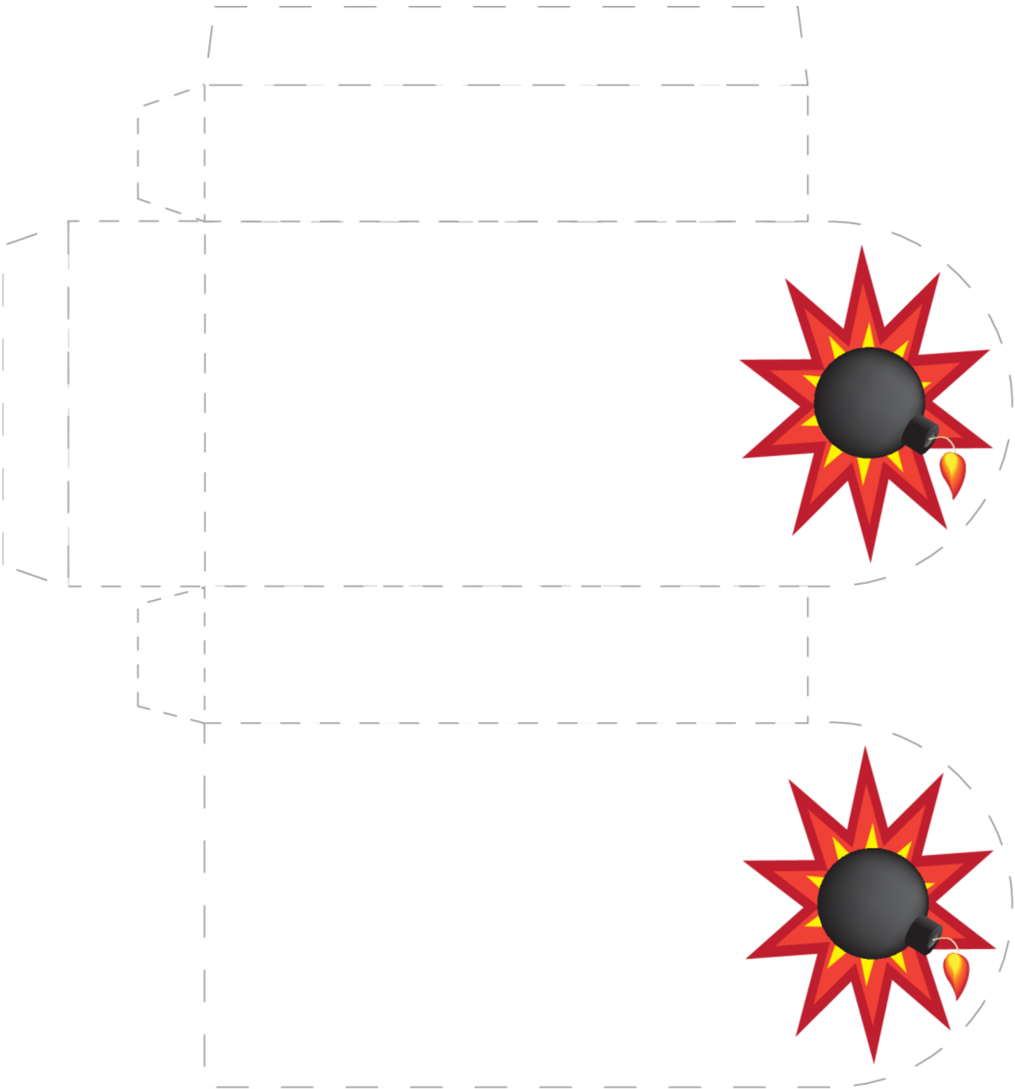
- In order to make it easier for the students to transition to the concept of states, we recommend a discussion of the concept of states based on Schrödinger's cat. The system consists of a box, a cat, and a poison that is released upon the decay of a radioactive atom (a random process). The system has 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 quantum physics interference and which-path experiments, 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.

- Often, the sentence "the photon interferes with itself" is used to concisely describe this type of experiment. In the broadest sense, whether one uses this or not is a matter of taste. When using this sentence, however, one should be aware of the very problematic implications: although a photon is an *elementary* excitation of the electromagnetic field, the sentence suggests that it is divisible and could interfere with itself. However, this is not the case! Because it is actually the possible *states* which interfere with one another, and which can be described mathematically and physically by their wave functions Ψ.
- In many educational models, the probability density $|\Psi(x,t)|^2$ is used as a quantity in order to explain the physical processes. If one considers the development of this function over time, a wave package first propagates from the laser onto the first beam splitter. Here, $|\Psi|^2$ separates into two parts, each of which propagates into one arm of the interferometer. If one approaches the interference and the which-path experiment with this didactic method, one should take care to heavily emphasize the indivisibility of a photon. Otherwise, there is a risk that the students will too greatly associate the probability density with the position of the photon – and therefore that the photon becomes divisible in the mind of the student.
- The discussion of the bomb tester with individual photons makes it possible to discuss many additional topics of quantum physics. Examples of suitable content include the entanglement of photons, the secure exchange of data by means of quantum communication, and the quantum eraser.

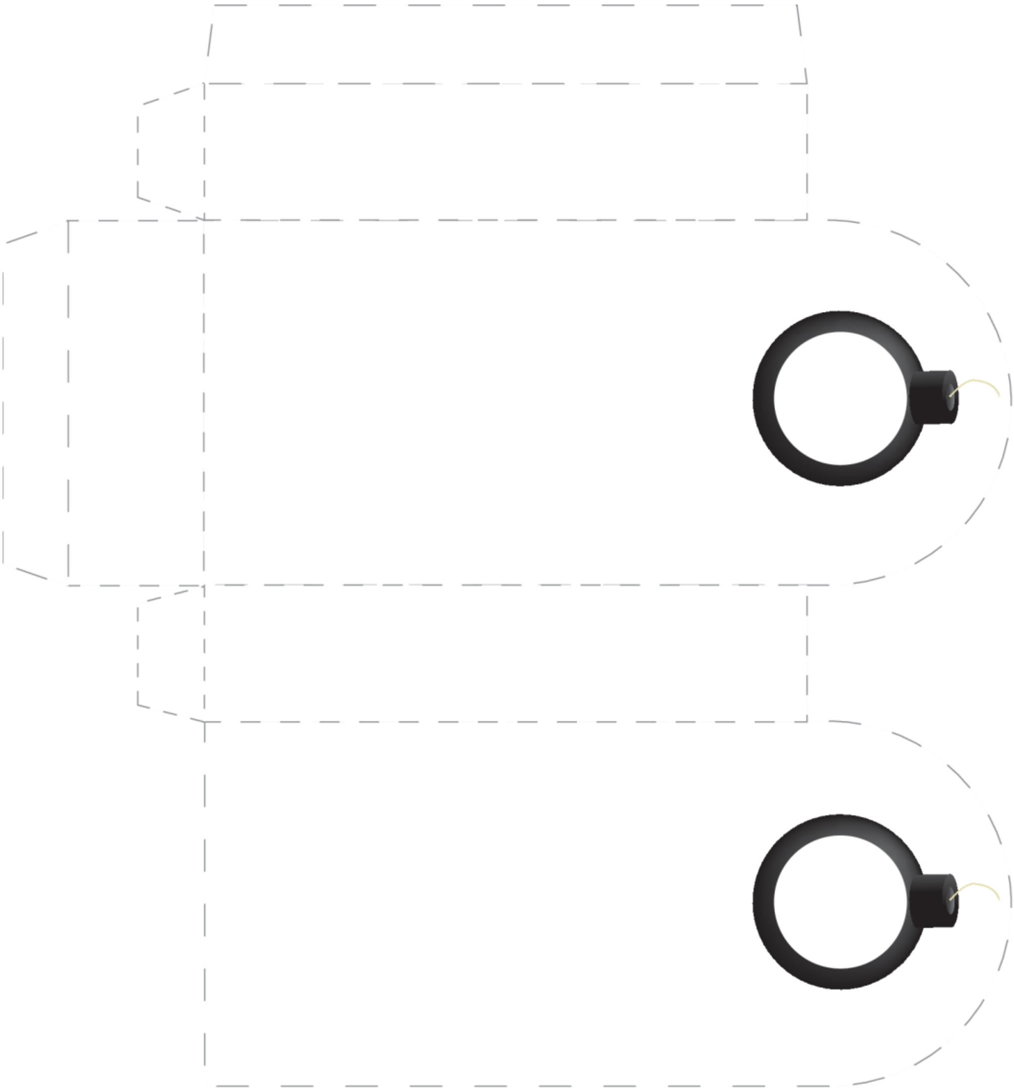
Active Bomb Model

This model bomb can be used to block the beam in an arm of the interferometer for the experiments described in Section 5.2. Cut out the shape along the outer edges. Fold along the dashed lines to create a box and use a piece of tape to secure the side flap.



"Dud" Bomb Model

This bomb model can be used to demonstrate the effects of a dud. Cut out the white center of the bomb and create a box as for the previous model. The laser beam can now pass through the bomb, i.e., it does not interact with it, thus simulating the behavior of a dud.



Chapter 7 Troubleshooting

- *The laser spots superpose, but there is no interference.*

  Do you see flickering in the superposition? If not, check whether all of the components have been positioned as precisely as possible (Is there a 90° beam angle after reflection? Is the height of the beam above the plate at the screen the same as it is directly at the laser?). If these conditions exist, you may have to simply experiment a little and slightly change one spot repeatedly without completely losing the superposition.

- *You have found an interference pattern, but the diameter is very small.*

  If this is the case, it is probable that the distance between the beam splitter and the mirror in one of the arms of the interferometer is much greater than in the other arm Therefore, move the mirror so that the distances are as equal as possible.

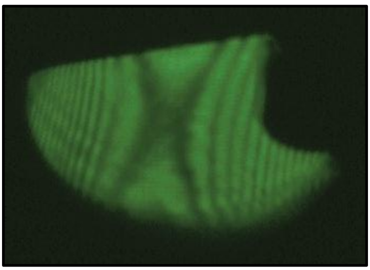
- *The interference sometimes disappears for no apparent reason without the setup being touched.*

  Temperature changes in the semiconductor can lead to changes in the laser modes. Place a hand on the laser module and warm it slightly – the interference should appear again.

- *The interference patter has low contrast.*

  The laser module emits more than one frequency mode which leads to a beating pattern. Move one of the mirrors forward or backward along the beam by about 1 mm.

- *Instead of the ring-shaped interference pattern, hyperbolic-shaped interference fringes can be seen.*

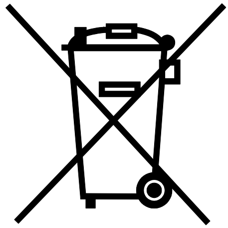
  In case of very small path length differences between both arms, any small phase change caused by imperfections in the optical beam path becomes dominant. In this case, the pattern is caused by the surface of the economy beam splitter having a slightly bent shape. The best way to avoid such effects would be using a cube beamsplitter. As the different shape of the pattern does not change any of the physics phenomena discussed in the bomb tester, our design uses the cost-efficient EBS1.

  The ring pattern can be obtained by moving one mirror about 1-2 mm in any direction along the beam path. This way, the phase difference from the different arm length dominates any other effects.

Chapter 8 Regulatory

As required by the WEEE (Waste Electrical and Electronic Equipment Directive) of the European Community and the corresponding national laws, Thorlabs offers all end users in the EC the possibility to return “end of life” units without incurring disposal charges.

- This offer is valid for Thorlabs electrical and electronic equipment:
- Sold after August 13, 2005
- Marked correspondingly with the crossed out “wheelie bin” logo (see right)
- Sold to a company or institute within the EC
- Currently owned by a company or institute within the EC
- Still complete, not disassembled and not contaminated



Wheelie Bin Logo

As the WEEE directive applies to self contained operational electrical and electronic products, this end of life take back service does not refer to other Thorlabs products, such as:

- Pure OEM products, that means assemblies to be built into a unit by the user (e.g. OEM laser driver cards)
- Components
- Mechanics and optics
- Left over parts of units disassembled by the user (PCB’s, housings etc.).

If you wish to return a Thorlabs unit for waste recovery, please contact Thorlabs or your nearest dealer for further information.

8.1. Waste Treatment Is Your Own Responsibility

If you do not return an “end of life” unit to Thorlabs, you must hand it to a company specialized in waste recovery. Do not dispose of the unit in a litter bin or at a public waste disposal site.

8.2. Ecological Background

It is well known that WEEE pollutes the environment by releasing toxic products during decomposition. The aim of the European RoHS directive is to reduce the content of toxic substances in electronic products in the future.

The intent of the WEEE directive is to enforce the recycling of WEEE. A controlled recycling of end of life products will thereby avoid negative impacts on the environment.

Chapter 9 Thorlabs Worldwide Contacts

For technical support or sales inquiries, please visit us at www.thorlabs.com/contact for our most up-to-date contact information.

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THORLABS

Discovery

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

User Guide

Table of Contents

Chapter 1 Warning Symbol Definitions

Below is a list of warning symbols you may encounter in this manual or on your device.

Symbol	Description
	Direct Current
	Alternating Current
	Both Direct and Alternating Current
	Earth Ground Terminal
	Protective Conductor Terminal
	Frame or Chassis Terminal
	Equipotentiality
	On (Supply)
	Off (Supply)
	In Position of a Bi-Stable Push Control
	Out Position of a Bi-Stable Push Control
	Caution: Risk of Electric Shock
	Caution: Hot Surface
	Caution: Risk of Danger
	Warning: Laser Radiation

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.

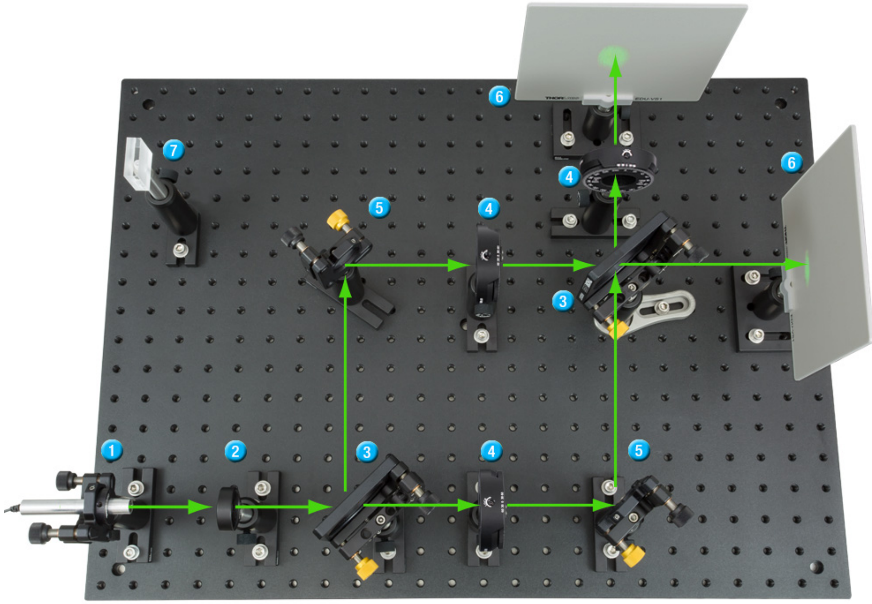


Figure 1 Mach-Zehnder Interferometer Setup and Diagram, Including (1) Laser, (2) Lens, (3) Beamsplitters, (4) Polarizers, (5) Mirrors, (6) Viewing Screens, and (7) Alignment Tool

Chapter 4 Setup

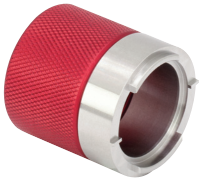
4.1. Components and Parts List

In cases where the metric and imperial kits contain parts with different item numbers, metric part numbers and measurements are indicated by parentheses unless otherwise noted.

 1 x **CPS532-C2**[1] 532 nm Laser Diode Module	 1 x **LDS5(-EC)** 5 VDC Laser Power Supply	 1 x **AD11NT** Ø2" (50.8 mm) Unthreaded Adapter for Ø11 mm Cylindrical Components
 1 x **LB1901** Ø1" Lens, f = 75 mm	 1 x **LMR1(/M)** Ø1" Lens Mount	 2 x **EBS2** Ø2" 50:50 Beamsplitter
 2 x **KM200T** Ø2" Beamsplitter Mount	 1 x **LPVISE2X2** (Stamped into 3 Ø1" Circles) Linear Polarizer	 3 x **RSP1D (/M)** Ø1" Rotating Polarizer Mounts

[1] The CPS532-C2 is a low power, Class 2 version of our Class 3 CPS532 laser diode module.

 2 x **ME1-G01** Ø1" Aluminum Mirror	 3 x **KM100** Kinematic Ø1" Mirror Mount	 2 x **EDU-VS1(/M)** Viewing Screen
 10 x **TR3 (TR75/M)** Ø1/2" (Ø12.7 mm) Mounting Post, 3" (75 mm) Long	 9 x **PH3 (PH75/M)** Ø1/2" (Ø12.7 mm) Post Holder, 3" (75 mm) Long	 2 x **TR2 (TR50/M)** Ø1/2" (Ø12.7 mm) Mounting Post, 2" (50 mm) Long, for Viewing Screen
 2 x **PH2 (PH50/M)** Ø1/2" (Ø12.7 mm) Post Holder, 2" (50 mm) Long, for Viewing Screen	 8 x **BA1(/M)** Mounting Base, 1" x 3" x 3/8" (25 mm x 58 mm x10 mm)	 2 x **BA2(/M)** Mounting Base, 2" x 3" x 3/8" (50 mm x 75 mm x 10 mm)
 1 x **PH3E (PH75E/M)** Ø1/2" (Ø12.7 mm) Pedestal Post Holder, 3.19" (80.9 mm) Long	 1 x **CF125** Clamping Fork, 1.24" (31.5 mm) Counterbored Slot	 1 x **BA1S(/M)** Small Mounting Base, 1" x 2.3" x 3/8" (25 mm x 58 mm x 10 mm)

 1 x **MB1824 (MB4560/M)** Aluminum Breadboard, 18" x 24" (45 cm x 60 cm)	 1 x **RDF1** 4 Rubber Breadboard Feet	 1 x **SM1RR** SM1-Threaded Retaining Ring
 4 x **F25SSK1-GOLD** Gold Adjuster Knob	 1 x **AT1(/M)** Acrylic Alignment Tool, 1.18" x 1.18" (30.0 mm x 30.0 mm)	 1 x **SPW606** SM1 Spanner Wrench, 1" (25.4 mm) Long

Imperial Kit

Type	Quantity	Type	Quantity
1/4"-20 x 1/2" Cap Screw	11	1/4" Nut	4
1/4"-20 x 5/8" Cap Screw	11	1/4" Washer	11
1/4"-20 x 3/4" Cap Screw	4	 1 x **BD-3/16L** Balldriver for 1/4"-20 Screws	
8-32 Screws Included with Mounts			
1 x Hex Key for 8-32 Cap Screws (9/64″), 1x Hex Key for 8-32 Set Screws (5/64"), 1 x Hex Key for 6-32 Set Screws (1/16")			

Metric 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 Cap Screws (3mm), 1 x Hex Key for M4 Set Screw (2mm), 1 x Hex Key for M3 Set Screw (1.5mm)			

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.

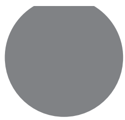
Figure 3 Mounting the KM100(/M) and KM200T on a Post

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. Remove the two protective films on the actual polarizer film – in this case you should wear gloves and not touch the polarizer film itself. It is very helpful to place a piece of adhesive tape over the edge of the film. When removing the tape, the protective film is pulled off as well. To get a grip on the protective film it might be necessary to cut along the flat edge of the film with scissors and use tweezers
7. 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.



8. 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.

9. 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.

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

11. 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, $\varphi = 277° - 143° = 134°$

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

13. 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:

14. 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:

15. 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:

16. 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.

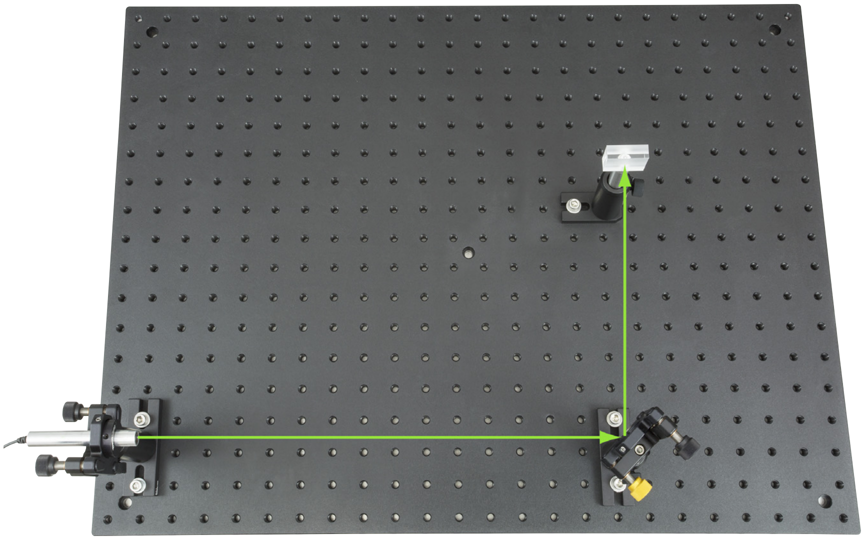


Figure 4 Laser Setup

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.

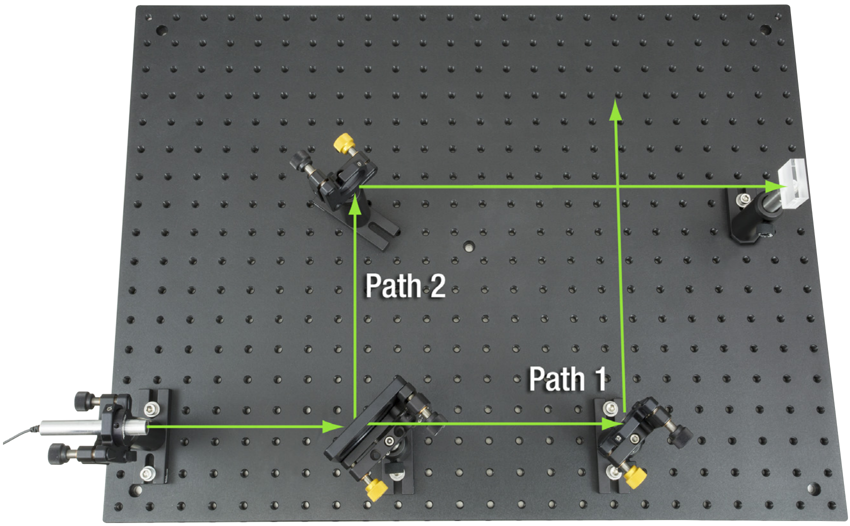


Figure 5 Mirror and Beamsplitter Setup

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.

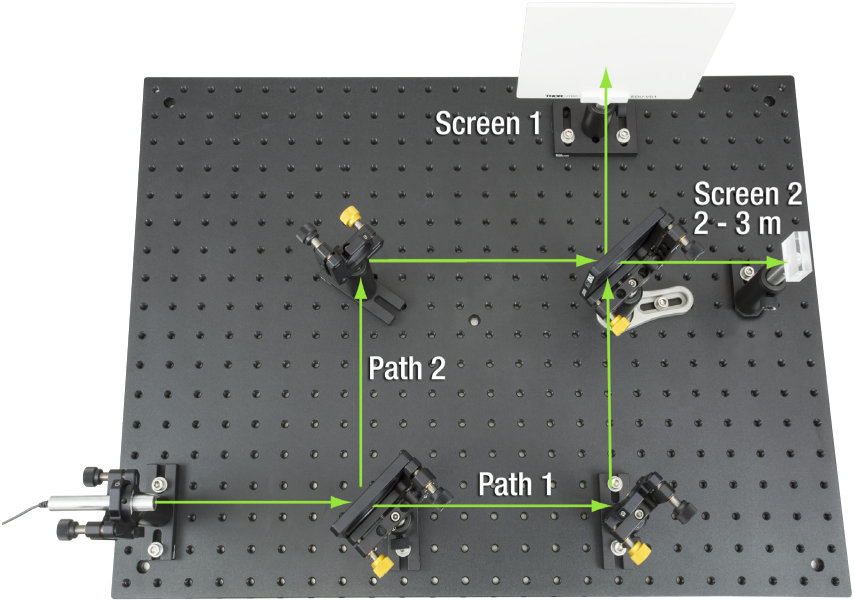


Figure 6 Screens and Alignment

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.

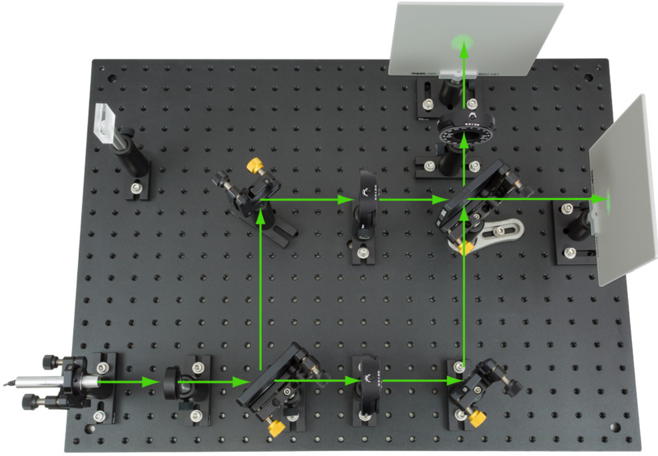


Figure 7 Interferometer Final Setup

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.

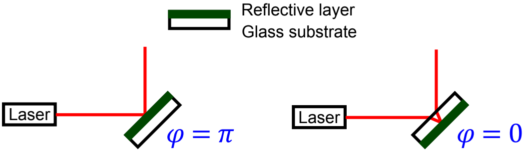


Figure 8 Phase Shifts at a Plate Beamsplitter

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

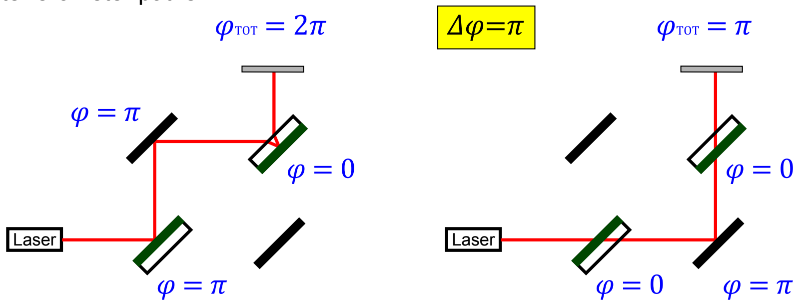


Figure 9 Phase Difference at One Screen

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

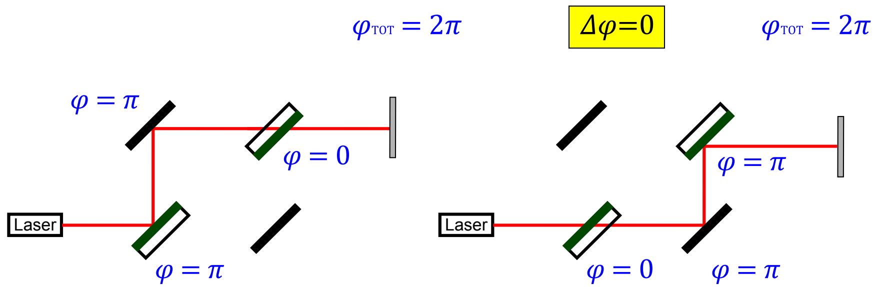


Figure 10 Phase Difference at Other Screen

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

Note: In this discussion, we neglect 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.

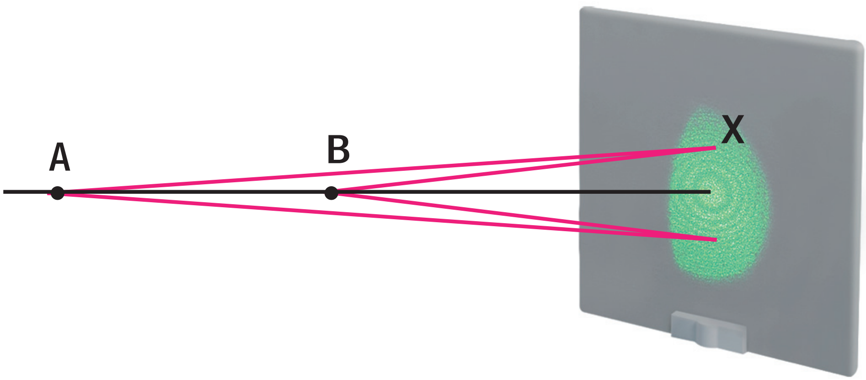


Figure 11 Explanation of a Circular Interference Pattern

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).

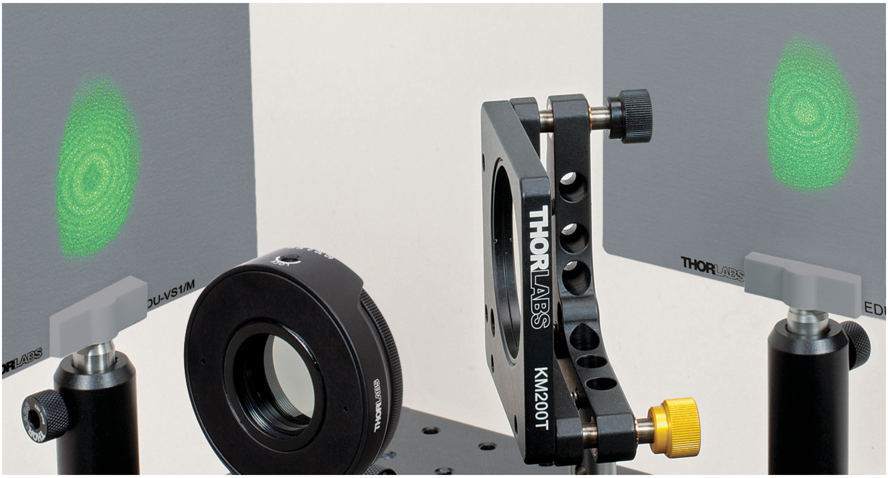


Figure 12 Interference Patterns

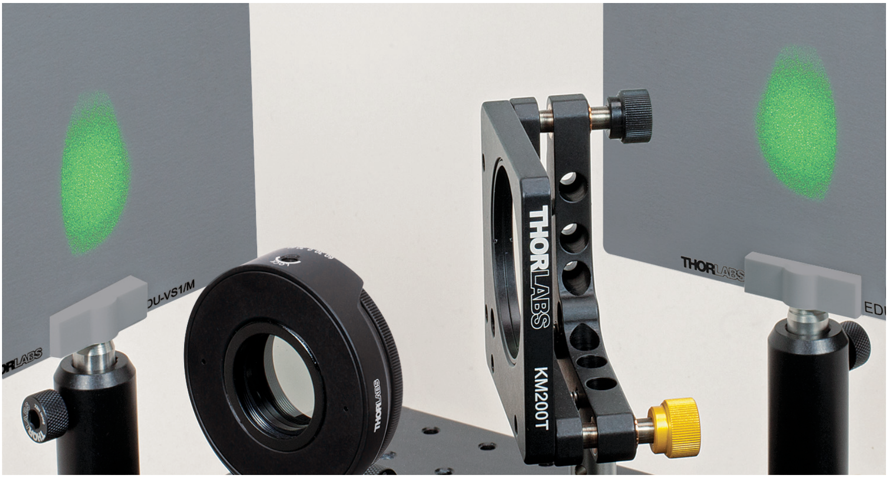


Figure 13 Disappearance of the Interference Pattern

Trick 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 1, an interference pattern appears again. Figure 1 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:

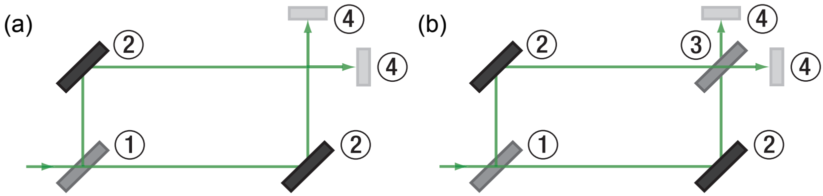


Figure 15 (a) Sketch of the Setup without the Second Beamsplitter, (b) Setup with Second Beamsplitter, (1) First Beamsplitter, (2) Mirror, (3) Second Beamsplitter, (4) Screens.

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.

- **Does the Photon Interfere with Itself?**

  Often the sentence "the photon interferes with itself" is used to concisely describe this type of experiment. In the broadest sense, whether one uses this or not is a didactical matter of taste. When using this sentence, however, one should be aware of the very problematic implications: although a photon is an *elementary* excitation of the electromagnetic field, the sentence suggests that it is divisible and could interfere with itself. However, this is not the case! It is actually the possible *states* which interfere with one another, which can be described mathematically-physically by their wave functions Ψ.

- **Probability Density**

  In many didactic models, the probability density $|\Psi(x, t)|^2$ is used as a quantity in order to explain the physical processes. If one considers the development of this function over time, a wave package first propagates from the laser onto the first beamsplitter. Here, $|\Psi|^2$ separates into two parts, each of which propagates into one arm of the interferometer. If one approaches the quantum eraser experiment with this didactic method, one should take care to heavily emphasize the indivisibility of a photon. Otherwise, there is a risk that the students will too greatly associate the probability density with the position of the photon – and therefore that the photon becomes divisible in the mind of the student.

- **Additional Quantum Physics Topics**

  The discussion of the quantum eraser with individual photons makes it possible to discuss many additional topics of quantum physics. Examples of content are particularly the entanglement of photons, the secure exchange of data by means of quantum communication, and the interference-free quantum measurement ("bomb tester").

Chapter 7 Troubleshooting

- **The laser spots superimpose, but there is no interference.**

  Do you see flickering in the superposition? If not, check whether all components have been positioned as precisely as possible, including a 90° beam angle after all reflections. Is the height of the beam above the plate at the beamsplitters, at the mirrors and at the screens the same as it is directly at the laser? If these conditions exist, you may have to simply experiment a little and slightly change one spot repeatedly without completely losing the superposition.

- **The interference sometimes disappears for no apparent reason without the setup being touched.**

  Temperature changes in the crystal inside the laser can lead to changes in the laser modes. Place a hand on the laser module and warm it slightly – the interference should appear again.

- **Instead of the ring-shaped interference pattern, hyperbolic-shaped interferences can be seen (as in Figure 16, below).**

  These and other distortions of the interference pattern especially occur when the height of the beams along both arms of the interferometer is not exactly the same. Make sure that the beam height is the same after each optical element. Also ensure that the beam is reflected off each element in a 90° angle. Unfortunately, there is no known operational procedure that changes the interference pattern from the hyperbolic shapes to concentric circles.
  Important Note:
  Naturally, all of the physics behind the quantum eraser experiment, both classical and quantum mechanical, is valid even if the interference pattern does not show rings. Therefore, the quantum eraser experiment may be demonstrated and discussed just as effectively with the interference pattern displayed in Figure 16.

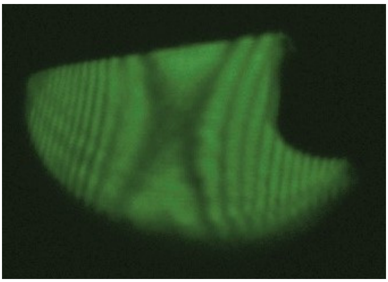


Figure 16 Hyperbolic Interference Patterns

Chapter 8 Further Ideas

- The parts contained in this kit can also be used to set up a Michelson-Interferometer. For that, use only one beamsplitter and place the two mirrors so that they reflect the laser back towards the beamsplitter. For a more detailed description with images see the manual of the EDU-BT1(/M) bomb tester.
- The following ideas are based on the feedback of Dr. Mark Colclough, Director of Laboratory Learning and Teaching, School of Physics and Astronomy, University of Birmingham, UK: In order to obtain quantitative measurements of the interference pattern, he uses a ground glass screen in place of one of the plastic ones, and images the fringe pattern using a webcam with an added close-up lens. Thorlabs offers unmounted ground glass diffusers which can be mounted by using, e.g., the FP02 wide plate holder. The camera used by Dr. Colclough is a C270 Logitech Webcam (for reasons of manual exposure control, the removable lens and an economic price). Image analysis then enables the students to quantitatively measure the fringe contrast as a function of polarisation, and compare the fringes with the theoretical form.

  Since we did not test this setup, we cannot guarantee for the obtained results.

Chapter 9 Regulatory

As required by the WEEE (Waste Electrical and Electronic Equipment Directive) of the European Community and the corresponding national laws, Thorlabs offers all end users in the EC the possibility to return "end of life" units without incurring disposal charges.

- This offer is valid for Thorlabs electrical and electronic equipment:
- Sold after August 13, 2005
- Marked correspondingly with the crossed out "wheelie bin" logo (see right)
- Sold to a company or institute within the EC
- Currently owned by a company or institute within the EC
- Still complete, not disassembled and not contaminated

Wheelie Bin Logo

As the WEEE directive applies to self contained operational electrical and electronic products, this end of life take back service does not refer to other Thorlabs products, such as:

- Pure OEM products, that means assemblies to be built into a unit by the user (e.g. OEM laser driver cards)
- Components
- Mechanics and optics
- Left over parts of units disassembled by the user (PCB's, housings etc.).

If you wish to return a Thorlabs unit for waste recovery, please contact Thorlabs or your nearest dealer for further information.

9.1. Waste Treatment is Your Own Responsibility

If you do not return an "end of life" unit to Thorlabs, you must hand it to a company specialized in waste recovery. Do not dispose of the unit in a litter bin or at a public waste disposal site.

9.2. Ecological Background

It is well known that WEEE pollutes the environment by releasing toxic products during decomposition. The aim of the European RoHS directive is to reduce the content of toxic substances in electronic products in the future.

The intent of the WEEE directive is to enforce the recycling of WEEE. A controlled recycling of end of life products will thereby avoid negative impacts on the environment.

Chapter 10 Thorlabs Worldwide Contacts

For technical support or sales inquiries, please visit us at www.thorlabs.com/contact for our most up-to-date contact information.

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