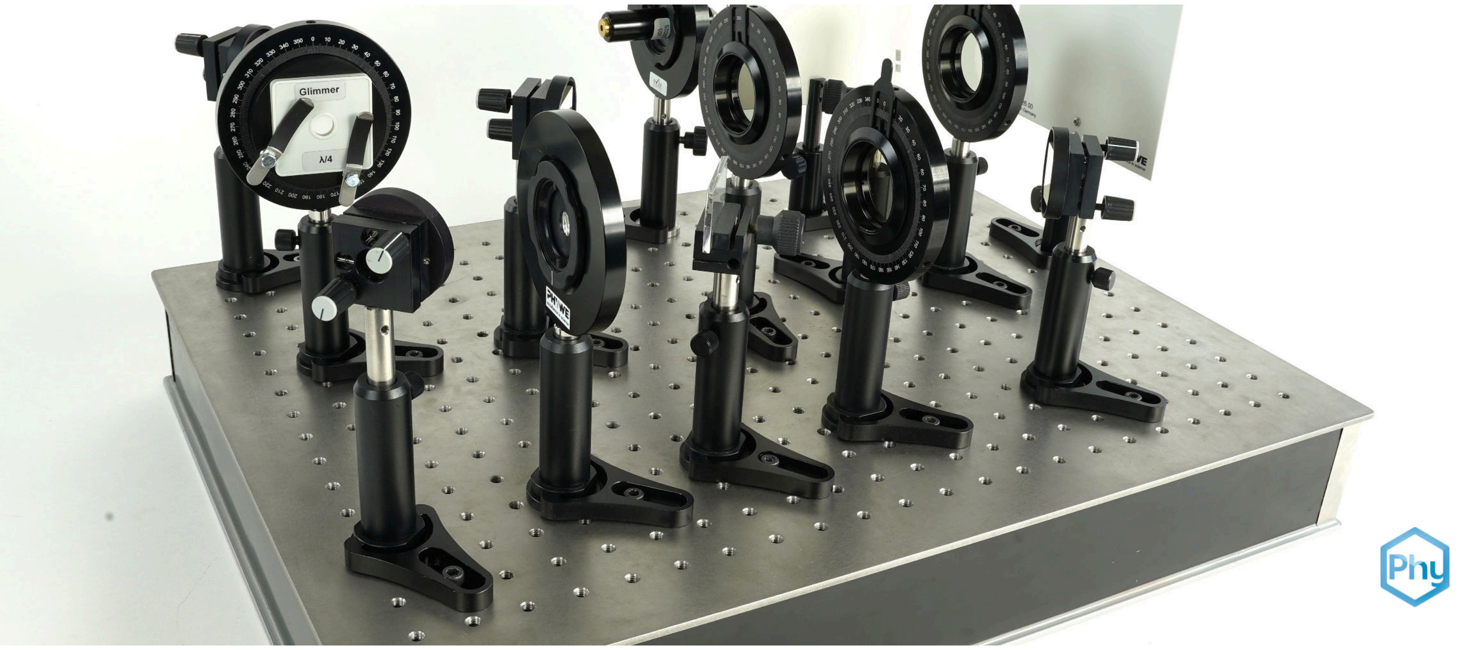
# Quantum eraser with the Mach-Zehnder interferometer




Physics > Modern Physics > Quantum physics

| Difficulty level | Group size | Preparation time | Execution time |
| --- | --- | --- | --- |
| - | - | 45+ minutes | 45+ minutes |

This content can also be found online at:

http://localhost:1337/c/67408c84dccbab000279f45c

# General information

## Application

Setup

The quantum eraser is a concept from quantum physics, where measurement alters the wave-particle duality of entangled particles. This demonstrates the paradox of quantum phenomena, where a particle exhibits both wave-like and particle-like behavior depending on whether information about it is measured or not. The application of the quantum eraser lies in research on quantum communication, quantum encryption, quantum computing, and fundamental investigations of quantum mechanics. It has the potential to enhance our understanding of quantum technologies and enable novel applications.



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## Other information (1/2)

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**Prior knowledge**

The proir knowlege required for this experiment can be found in the theory section.

**Main principle**

A Mach-Zehnder-interferometer is illuminated with a laser beam. Circular inteference ringes appear on the screens behind the interferometer. If polarization filters with opposite polarization planes are placed in the two interferometer path the interference pattern disappears. Placing another polarization filter in front of one of the screens causes the pattern to reappear. Electromagnetic radiation kann be discribed both in terms of propagation waves, as well as particles (photons). The experiment illustrates this duality by showing how interference patterns can be explained on the basis of both classical wave mechanics and quantum physics.

## Other information (2/2)

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**Learning objective**

The goal of this experiment is to investigate the principle behind a Quantum Eraser.

**Tasks**

1. Set up the experiment and observe the interference pattern on the screen.

2. Change the polirization of the beam with the $P1$ and $P2$ polarizers and observe the influence on the interference pattern

3. Use the third polarizer $P3$ to cancel the polarization of the light in the two beams, and observe the reappearance of interference pattern.



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# Theory (1/6)

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### Classical physics - wave interference

Wave interference is the superposition of two or more waves that results in a new wave pattern. The resultant displacement at a point is equal to the vector sum of the displacements of different waves at that point. To illustrate this principle, let us assume two sinusoidal waves of the same wavelength interfere with each other. If the phase-shift between them is zero, in other words, if at any given point their amplitudes are the same, the overall amplitude will be double that of each wave (constructive interference). If, on the other hand, their phases are shifted by half a period, they will cancel each other out (destructive interference). The figure illustrates this example.

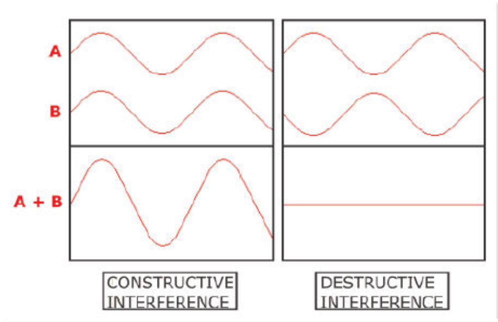


Illustration of wave interference

# Theory (2/6)

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Most electromagnetic waves can be well approximated by plane waves, that is waves with infinitely long and wide wavefronts. For such electromagnetic waves, it follows from Maxwell's equations that the electric and magnetic field are perpendicular to the direction of propagation and to each other. Electromagnetic waves exhibit a property called polarization, which describes the orientation of their oscillations. Conventionally, when considering polarization, only the electric field vector is described and the magnetic field is ignored, since it is perpendicular to the electric field and proportional to it.



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# Theory (3/6)

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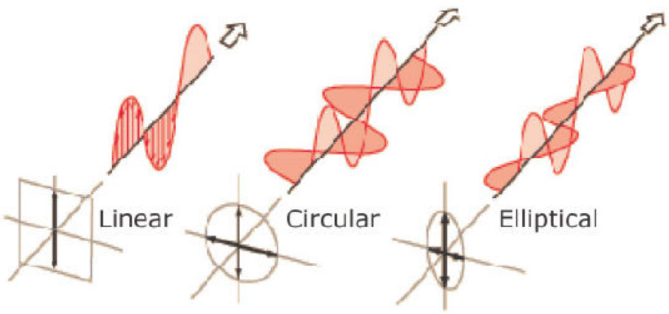
If we divide the electric field vector into $x$ and $y$ components, a polarization of a wave tells us how those components change in time. In other words, a polarization state of an electromagnetic wave is the shape traced out in a fixed plane by the electric vector as such a plane wave passes over it (see fig.). Important fact is that electromagnetic waves of different polarization do not interfere with each other.




Different polarisations of electromagnetic waves

# Theory (4/6)

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**Quantum physics - the quantum eraser**

The experiment can also be interpreted by a quantum theory. Hence, we now consider the electromagnetic radiation to consist of photons. Note, that this does not mean that we can think of photons as rigid spheres. Actually, in mathematical terms, a state of a system (a photon for example) in quantum mechanics is described by a complex wave function $\Psi(x,t)$ (also called a state vector in a complex vector space), belonging to a complex separable Hilbert space, and is governed by the Schrödinger equation (Eq. 1)

$$i\hbar\frac{\partial}{\partial t}\Psi(x,t) = \hat{H}\Psi(x,t) \qquad (1)$$

where $i$ is the complex number, $\hbar$ is the reduced Planck constant and $\hat{H}$ is the Hamiltonian operator.

The wave function $\Psi(x,t)$ is a rather abstract mathematical object and does not represent an observable, that is, a quantity we can actually measure. What we can obtain from the quantum theory is a probability density of an observable, which is given by the amplitude of the wave function. Hence, we can calculate the probability of finding a particle at a given position in space, or having a given momentum, or energy. etc.



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## Theory (5/6)

Therefore even though we talk about particles the quantum theory describes them as wave packets, and what we actually obtain are "clouds" of probability. For example, if we calculate a position of a photon, the result will be a region in space where the probability is non-zero, and not a single location, as in classical physics. What this means is that, from the quantum point of view, the particle is everywhere in the region where the calculated probability is non-zero.

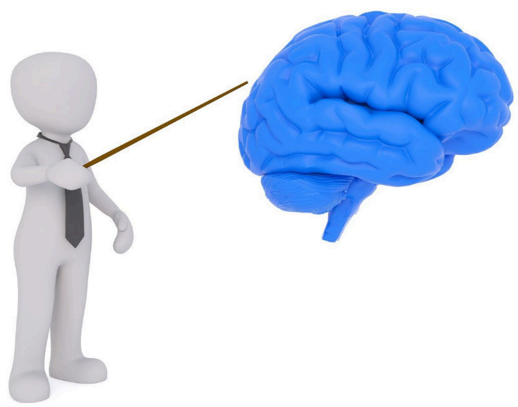
Additionally, the probability is given only by the amplitude of the wave function, while the phase encodes information about the interference between quantum states. This gives rise to the wave-like behavior of quantum states. For example, if there are two ways for a photon to travel, as in the quantum eraser experiment, and both are equally probable (we cannot measure which path the photon actually takes), both of these quantum states interfere with each other and result in the fringe pattern we observe contrary to classical mechanics, the quantum theory does not allow for accurate simultaneous predictions of conjugate variables, like position and momentum, time and energy (frequency).

## Theory (6/6)

This is known as the uncertainty principle (Eq. 2, for position and momentum)

$$\Delta x \Delta p >= \frac{\hbar}{2} \qquad (2)$$

where $\Delta x$ and $\Delta p$ are the uncertainty of position and momentum, respectively. Hence, a minimum exists for the product of the uncertainties, and the more precisely one property is measured, the less precisely the other can be measured.





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# Equipment

| Position | Material | Item No. | Quantity |
|---|---|---|---|
| 1 | Optical breadboard, optimized Damping | 08751-00 | 1 |
| 2 | YAG Laser green, 1 mW, 532 nm for component holder | 08767-99 | 1 |
| 3 | Surface mirror 30 x 30 mm | 08711-01 | 4 |
| 4 | Adjusting support 35 x 35 mm | 08711-04 | 4 |
| 5 | Beam splitter 1/1, non polarizing | 08741-00 | 2 |
| 6 | Holder for diaphragms and beam splitters beam height 15cm | 08719-01 | 2 |
| 7 | Screen, white, 150x150 mm | 09826-00 | 2 |
| 8 | Lens made of glass, biconvex, f = + 20 mm | 08059-00 | 1 |
| 9 | Component holder | 08043-00 | 2 |
| 10 | Polarization specimen, mica | 08664-00 | 1 |
| 11 | Universal Holder, rotational | 08040-02 | 1 |
| 12 | Polarisation filter on stem | 08610-02 | 3 |
| 13 | Ring for component holder | 08044-00 | 2 |



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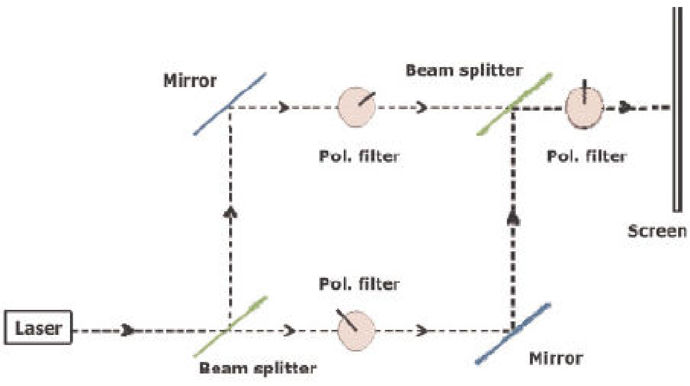
# Setup and Procedure

## Setup (1/7)




Schematic diagram of the beam paths

In this experiment a Mach-Zehnder Interferometer is used to split a light beam into two parts, send them along two different paths where they can be subjected to individual treatment and then to reunify the two beams again and observe interference effects (see fig.). Since the precise alignment of the interferometer is crucial, the individual steps will be described in the following and illustrated with photographs.



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## Setup (2/7)

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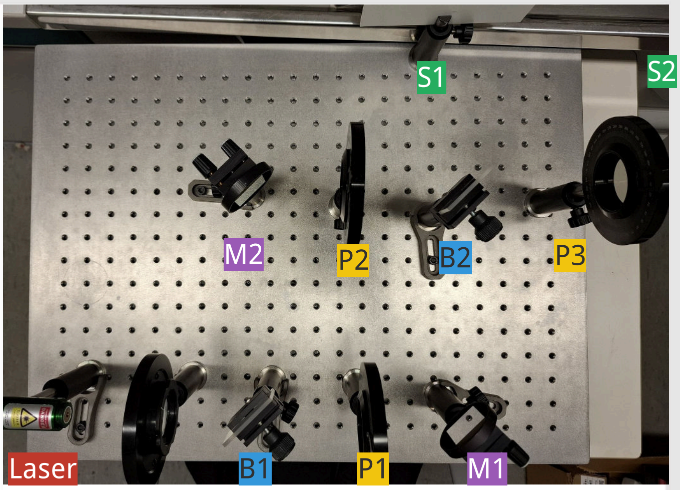
- The final set-up is shown in Fig. 4 the position of all the optical elements can be seen along with the names and abbreviations used for them in this set-up guide.

  **Note:** Once the optical component is mounted on a foot and correctly positioned on the optical base plate, tightly clamp the foot to avoid unwanted movement.

  **Caution:** Never look directly into a non-attenuated laser beam.




Final setup, top view

## Setup (3/7)

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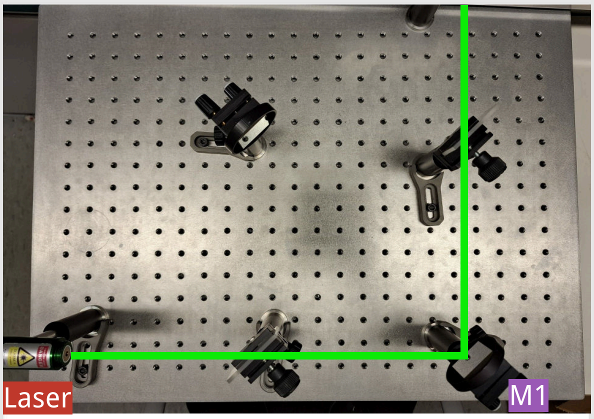
- Place the laser in a corner of the breadboard, turn it on and align the laser beam parallel to a row of holes on the breadboard.
- Position a mirror **M1** in the laser beam's path.
- Adjust the mirror until the laser beam is centered on it. Using a card or a sheet of paper can help with this step.
- Loosen the mirror post and rotate it to align the reflected beam roughly parallel to a row of holes on the breadboard. Ensure the reflected beams are perpendicular to each other. This is a crucial step.




Adjusting laser and mirror M1



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## Setup (4/7)

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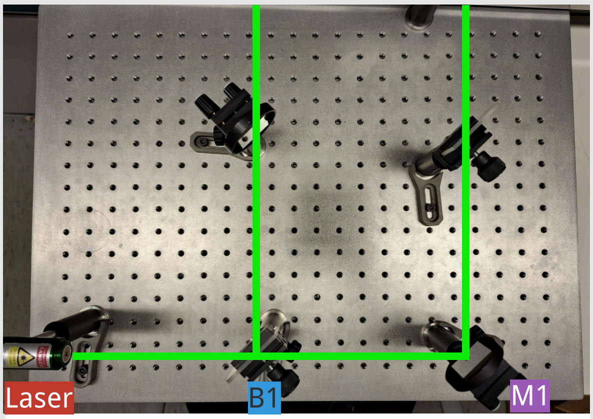
- Position a beam splitter **B1** between the laser and the mirror **M1**.
- Adjust its position until the laser beam is centered on the beam splitter.
- Rotate the beam splitter so that the beam aligns parallel to a row of holes.




Adjusting beam splitter B1

## Setup (5/7)

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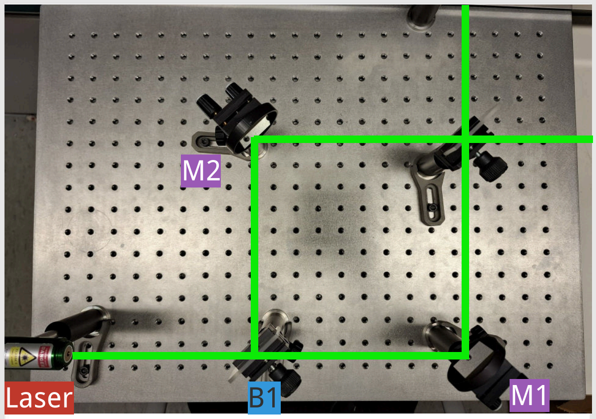
- Place a second mirror **M2** approximately 20 cm away in the path of the beam reflected from the beam splitter.
- Center the beam on this mirror, and rotate it so the reflected beam runs parallel to the breadboard's rows, maintaining a 90° angle with the other beam.




Adjusting mirror M2



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## Setup (6/7)

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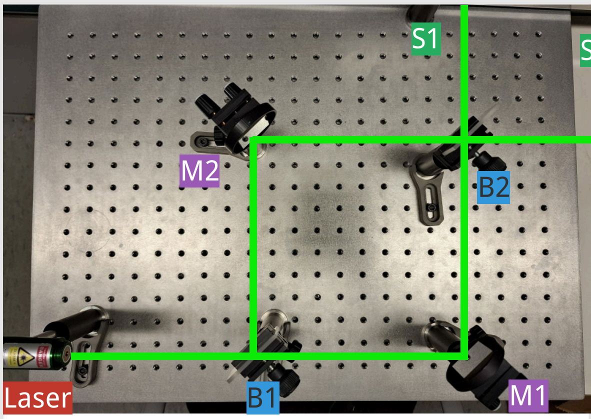
- Place the second beam splitter **B2** near the opposite corner of the breadboard. Add two screens to the setup: one close behind the second beam splitter and the other around 2 meters away.
- Carefully adjust the second beam splitter to ensure the two laser beams reflected from the mirrors overlap.
- Verify that the two laser beams overlap both on the second beam splitter and on the two screens:
  It is important that the adjustment is only done when the points coincide on both screens (the close one and the far one) simultaneously!




Adjusting beam splitter B2 and screens

## Setup (7/7)

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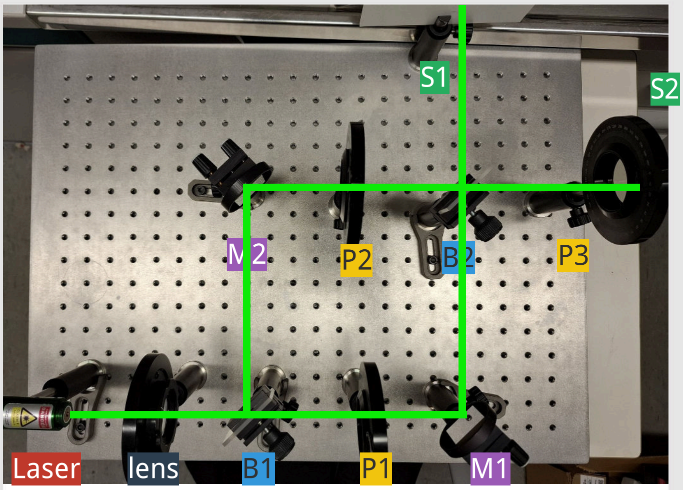
- Place the expansion lens ($f = 20\,\text{mm}$) behind the laser.
- Use the fine adjustments on the mirrors to overlap the beams precisely until interference patterns are visible on both screens.
- A twinkling of these bright spots then already indicates interference effects.
- Place the three polarizing filters as shown in figure.




Final setup, top view



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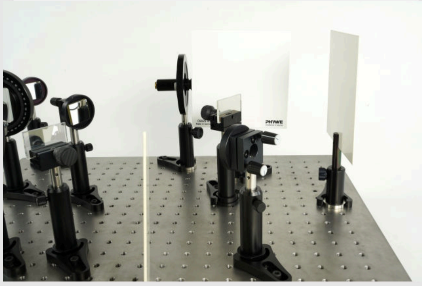
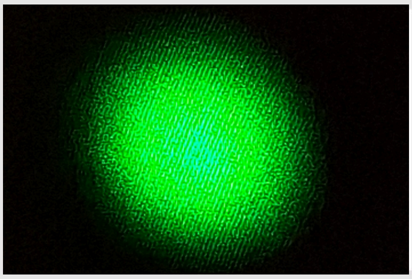
## Procedure (1/2)

*a) Qualitative investigation of interference*

Having set the experiment as described above, with the Mach-Zehnder setup the essential effects of interference can be demonstrated impressively and easily:

- If you block one of the two paths in the interferometer, on the screens a relatively homogeneous spot is visible. If you open now the blocked path, the spot does not become brighter everywhere, but there are regions (rings) where the brightness drops. This means, adding light to more light can result in darkness. If one blocks only half of one path, direct comparison is possible as shown in the figures on the right.





## Procedure (2/2)

*b) Analogy experiment to a quantum eraser*

- Shift the polarizing filter $P3$ out of beam path. The polarizing filters $P1$ and $P2$ are oriented so that light passing them has the same polarization. Under these circumstances interference rings are visible on both screens.
- If you rotate $P1$ so that light passing it is polarized perpendicular to light passing $P2$ the interference effect on both screens vanishes. The quantum mechanical reason for this is, that now one could in principle determine which path in the interferometer a photon took by analysing its polarisation after it left the interferometer. The quantum information about the path of a photon, imposed upon it by the polarisors, destroys its ability to interfere.
- The next step is to introduce the polarizing filter $P3$ and orientate it at an angle of 45 degrees with respect to $P1$ and $P2$. The interference pattern is visible again on the screen behind $P3$ since it is not possible any more by analysing the photons arriving there, to determine which path they took in the interferometer.



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# Evaluation

## Evaluation (1/3)

*a) Qualitative investigation of interference*

The laser in the experiment produces coherent electromagnetic radiation, i.e. electromagnetic waves with the same frequency, polarization and phase. The beam is split into two, and the polarization of each beam can be changed separately by adjusting the polarizers $P1$ and $P2$. Hence, if we set the polarization of both beams to be the same (equivalent to removing the polarizes from the beam paths), we observe the interference pattern on the screens. The bright fringes are the locations where the incoming beams interfere constructively, hence producing higher amplitude than without the interference effect, while the dark fringes are the locations where destructive interference takes place, and the radiation from the two beams cancels each other out. When we use the polarizers $P1$ and $P2$ to set different polarizations for each beam, the interference pattern disappears, since electromagnetic waves of different polarization do not interfere. We can now use the third polarizer, $P3$, to recover the interference fringes by setting it at an angle of $45^\circ$ with respect to the polarizers $P1$ and $P2$. In doing so, we again bring the two beams to the same polarization, and they interfere.



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## Evaluation (2/3)

*b) Analogy experiment to a quantum eraser*

Now let us interpret the experiments using quantum physics. Even though the laser produces many photons that travel through the setup simultaneously, the truly amazing fact is that the result is the same (interference pattern is formed) even when we sent one photon at the time. From the quantum-mechanical point of view, the photon has non-zero probabilities of travelling along both paths in the setup, therefore it travels simultaneously along both paths and interferes with itself ! Both states (photon travelling along path a and path b) coexist and have the same probabilities, and the wave function is a superposition of those states, which results in the interference pattern.

## Evaluation (3/3)

*b) Analogy experiment to a quantum eraser*

When we use the polarization filters $P1$ and $P2$ to prescribe polarization information on the photon (opposite polarizations for each path), the wave function changes (and hence the probabilities of finding the photon along the two paths) and removes the ability of the photon to interfere with itself. What it means is that, by polarizing the photon, we are able to tell which path it travelled (the probability becomes one for one path and zero for the other) and hence only one state exists. Thus the interference pattern disappears. When we erase the polarization information with the third polarizer ($P3$), the probability of finding a photon at a given location at the detector (screen) results again from a superposition of the two equally probable quantum states (photon travelling along path a and path b), and hence forms the interference pattern. Thus the name “quantum eraser”.



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