Quantum Computing for the Quantum Curious

3.0 Creating Superposition: The Beam Splitter

3.0 Objectives

- Explain how light behaves like a particle in the single-photon beam splitter experiment.

- Show how the beam splitter creates a particle in a superposition state.

- Trace the path of light through a Mach–Zehnder interferometer from both a wave interference and a particle perspective.

3.1 Beam Splitter

In classical optics, a beam splitter acts like a partially reflective mirror that splits a beam of light into two. In a 50/50 beam splitter, 50% of the light intensity is transmitted and 50% is reflected, as shown in Fig. 3.1.

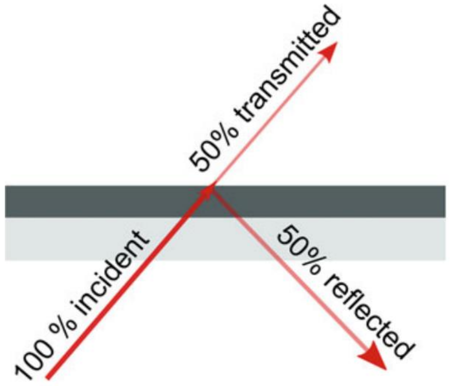


Fig. 3.1 A beam splitter reflects 50% of the incident light and transmits 50% of the incident light.

Visualization:

Imagine a barrier with holes, like Swiss cheese, placed in a pond. A water wave hitting this barrier creates smaller waves that pass through and reflect off the barrier. As shown in Fig.3.2.

Fig. 3.2 A beam splitter reflects 50% of the incident light and transmits 50% of the incident light.

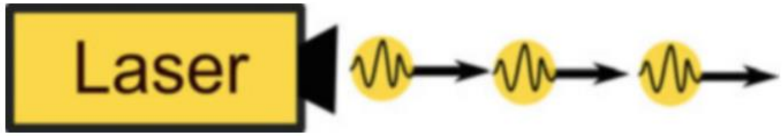
3.1 Beam Splitter

Question 1: What would happen if a classical particle such as a soccer ball is randomly kicked at the barrier? Assume the ball can fit through the holes.

- Classical Particle Behavior:
  - A classical particle like a soccer ball will either pass through one of the holes in the barrier or bounce back if it hits a solid part of the barrier.
  - The ball cannot be in two places at once, meaning it will take one definitive path.

- Comparison with Light Behavior:
  - Light behaves both as a wave and as a particle, Fig 3.3.
  - In the context of quantum mechanics, a photon can be in a superposition state, taking both paths until measured.
  - Classical particles, however, do not exhibit superposition.

Fig. 3.3 Low-intensity light is a stream of single photons.



3.1 Beam Splitter

Question 2 Open the beam splitter simulator,1 go to the Controls screen, and fire a single photon. The setup before the photon hits a beam splitter is shown in Fig. 3.4. Which detectors are triggered when the photon passes through the 50/50 beam splitter?

(a) Always detector 1

(b) Always detector 2

(c) Detector 1 OR detector 2

(d) Both detector 1 AND detector 2

(e) Neither

(C) When a single photon hits a 50/50 beam splitter, it enters a state of quantum superposition, where it can be found in either of the two paths (reflected or transmitted) but not both at the same time. The photon has a 50% probability of being detected by either detector.

3.1 Beam Splitter

Question 3 Which detector(s) would trigger if a classical wave is sent through the beam splitter?

(a) Always detector 1

(b) Always detector 2

(c) Detector 1 OR detector 2

(d) Both detector 1 AND detector 2

(e) Neither

(d) A classical wave, such as a continuous light wave, will split into two waves upon hitting a 50/50 beam splitter. Both detectors will receive part of the wave.

3.1 Beam Splitter

Question 4 Which detector(s) would trigger if a classical particle is sent through the beam splitter?

(a) Always detector 1
(b) Always detector 2
(c) Detector 1 OR detector 2
(d) Both detector 1 AND detector 2
(e) Neither

(c) A classical particle will either be reflected or transmitted by the beam splitter, but not both. It will end up at one of the detectors, but not both simultaneously.

3.1 Beam Splitter

Question 5 What does the photon do at the instance it encounters the 50/50 beam splitter?

(a) Splits in half. Half the photon is transmitted and half is reflected
(b) The whole photon goes through with 50% probability and reflects with 50% probability
(c) The whole photon is both transmitted and reflected, essentially in two places at once

(c) The photon is in a superposition of being both transmitted and reflected until it is measured, at which point it will be found in one path or the other.

3.2 Mach–Zehnder interferometer

To convince ourselves that the photon really did take two paths at once, let's see what happens when a second beam splitter is added.

This experimental setup is shown in Fig. 3.6. The mirrors redirect the photons towards the second beam splitter. This device configuration is known as a **Mach–Zehnder interferometer**.

What Happens:

1. **Photon Enters**: A single photon enters the first beam splitter.
2. **Superposition**: The photon enters a superposition, meaning it takes both paths simultaneously.
3. **Path Lengths**: The mirrors ensure that both paths are the same length (or differ by an exact multiple of the photon's wavelength).
4. **Interference**: At the second beam splitter, the two paths interfere with each other.
5. **Detection**: Due to interference, the photon always ends up at one specific detector (usually detector 1).

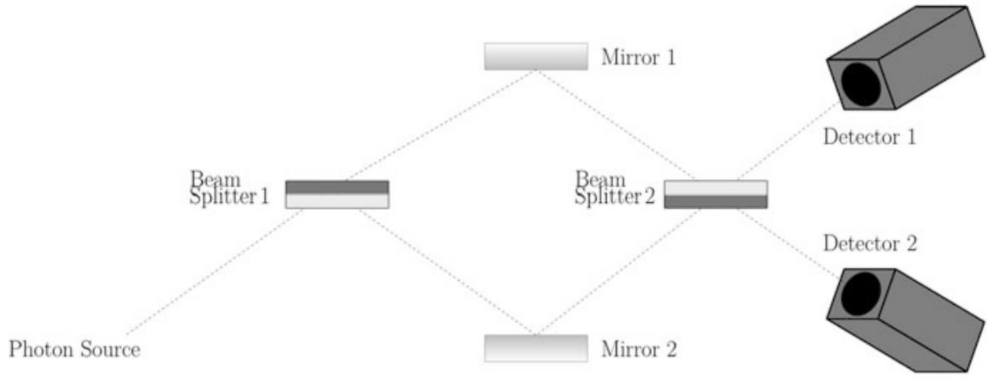


Fig. 3.6 Schematic of the Mach–Zehnder interferometer

3.2 Mach–Zehnder interferometer

Question 6 If we assume that the photon was reflected by the first beam splitter, which detectors would be triggered?

(a) Always detector 1
(b) Always detector 2
(c) Detector 1 OR detector 2
(d) Both detector 1 AND detector 2
(e) Neither

(a) Assuming the photon is reflected by the first beam splitter, it will follow a specific path. At the second beam splitter, depending on the path's phase shift, the photon will interfere constructively or destructively. If the paths lead to constructive interference at detector 1 and destructive interference at detector 2, only detector 1 will be triggered.

3.2 Mach–Zehnder interferometer

Question 7 If we assume that the photon was transmitted by the first beam splitter, which detectors would be triggered?

(a) Always detector 1
(b) Always detector 2
(c) Detector 1 OR detector 2
(d) Both detector 1 AND detector 2
(e) Neither

(a) Assuming the photon is transmitted by the first beam splitter, it will follow a different path. Again, the second beam splitter will cause interference depending on the phase shift of the path. Similar to the previous case, if the paths lead to constructive interference at detector 1 and destructive interference at detector 2, only detector 1 will be triggered.

3.2 Mach–Zehnder interferometer

Question 8 Construct the Mach–Zehnder interferometer in the beam splitter simulator and fire a single photon. Which detectors are triggered?

(a) Always detector 1
(b) Always detector 2
(c) Detector 1 OR detector 2
(d) Both detector 1 AND detector 2
(e) Neither

3.3 Big Ideas

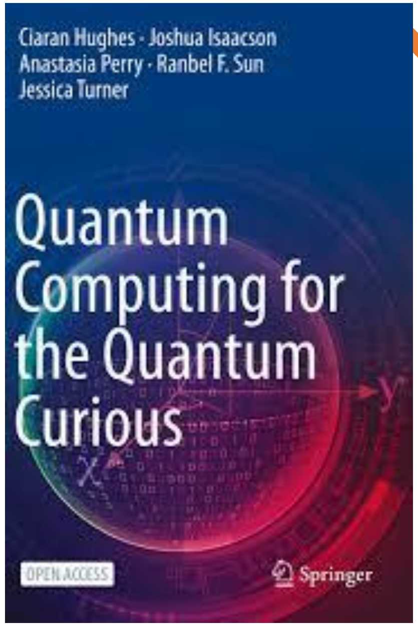
1. A photon can be put into a superposition using a beam splitter. After passing through the beam splitter, a photon takes both paths simultaneously.

2. The Mach–Zehnder interferometer shows how the photon really does take two paths at once. This is conclusive experimental evidence of superposition of photons.

Reference Book

Quantum Computing for the Quantum Curious

This open access book makes quantum computing more accessible than ever before. A fast-growing field at the intersection of physics and computer science, quantum computing promises to have revolutionary capabilities far surpassing "classical" computation. Getting a grip on the science behind the hype can be tough: at its heart lies quantum mechanics, whose enigmatic concepts can be imposing for the novice. This classroom-tested textbook uses simple language, minimal math, and plenty of examples to explain the three key principles behind quantum computers: superposition, quantum measurement, and entanglement.



Hughes, C., Isaacson, J., Perry, A., Sun, R. F., & Turner, J. (2021). Quantum computing for the quantum curious. In Springer eBooks. https://doi.org/10.1007/978-3-030-61601-4

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