

# Single Photon Interference

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November 26, 2010

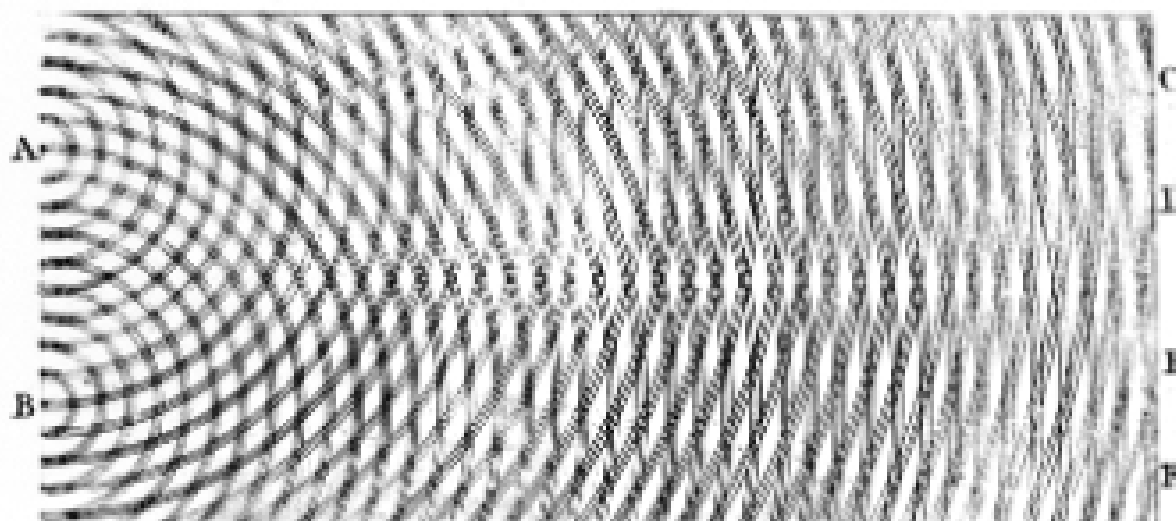
## Abstract

Our goal for this lab was to demonstrate the wave-particle duality of light as well as the effects of “which path” information on interference experiments. By highly attenuating a collimated laser beam produced by a 5 mW HeNe laser, we were able to observe an example of the wave-particle duality of light using a double slit apparatus. This was done by imaging the output of the double slit, observing both a graininess characteristic of low/single photon detection events and a clear double slit fringe pattern that shows the wave nature of light. Additionally, a Mach-Zehnder interferometer was employed to show the effects of “which path” information by polarizing light in each arm of the polarizer so that light from one arm was orthogonal to light from the other. We were unable to observe any interference from the interferometer unless we used an analyser polarizer to erase this “which path” information.

## 1 Background

The nature of light has been a major topic of interest to physics researchers throughout the past centuries. A major historical problem was whether light composed of waves or particles. This debate was largely settled in 1803 by Thomas Young [1].

The double slit experiment that Young is famous for demonstrated the wave nature of light. This classic experiment consists simply of a light source and a sheet with two slits cut in it. Light coming out of the slits diffract outward from each slit, and the light from one slit will constructively or destructively interfere with the light from the other based on the distance from the slits. This leads to an interference pattern, which is not compatible with a classical particle theory. Utilizing modern technology, this effect is easily seen by shining a collimated laser through a double slit onto a sheet, producing a distinctive fringe pattern that is indicative of constructive and destructive interference.



**Figure 1:** A sketch made by Thomas Young describing interference from double slit diffraction using water waves [2]. The sketch also applies to double slit diffraction using light, illustrating how light waves constructively and destructively interfere. Waves diffract from points A and B so that destructive interference occurs at points C, D, E, and F, resulting in minima in the fringe pattern.

Due to the results of Young's experiments and subsequent research, the wave theory of light dominated until the 20th century. This changed at the turn of the century, where discoveries such as the photoelectric effect showed that light apparently interacted with matter in only discrete quantities. Based on the photoelectric effect, Albert Einstein developed a model of light whereby light carried energy in discrete packets [3]. Such discrete packets of energy were later termed photons by chemist Gilbert Lewis in 1926. Einstein's model of light effectively brought a particle theory of light back to the attention of researchers, and the existence of photons was eventually confirmed through anti-bunching experiments. This aspect of light behaving both as a wave and a particle is referred to as wave-particle duality.

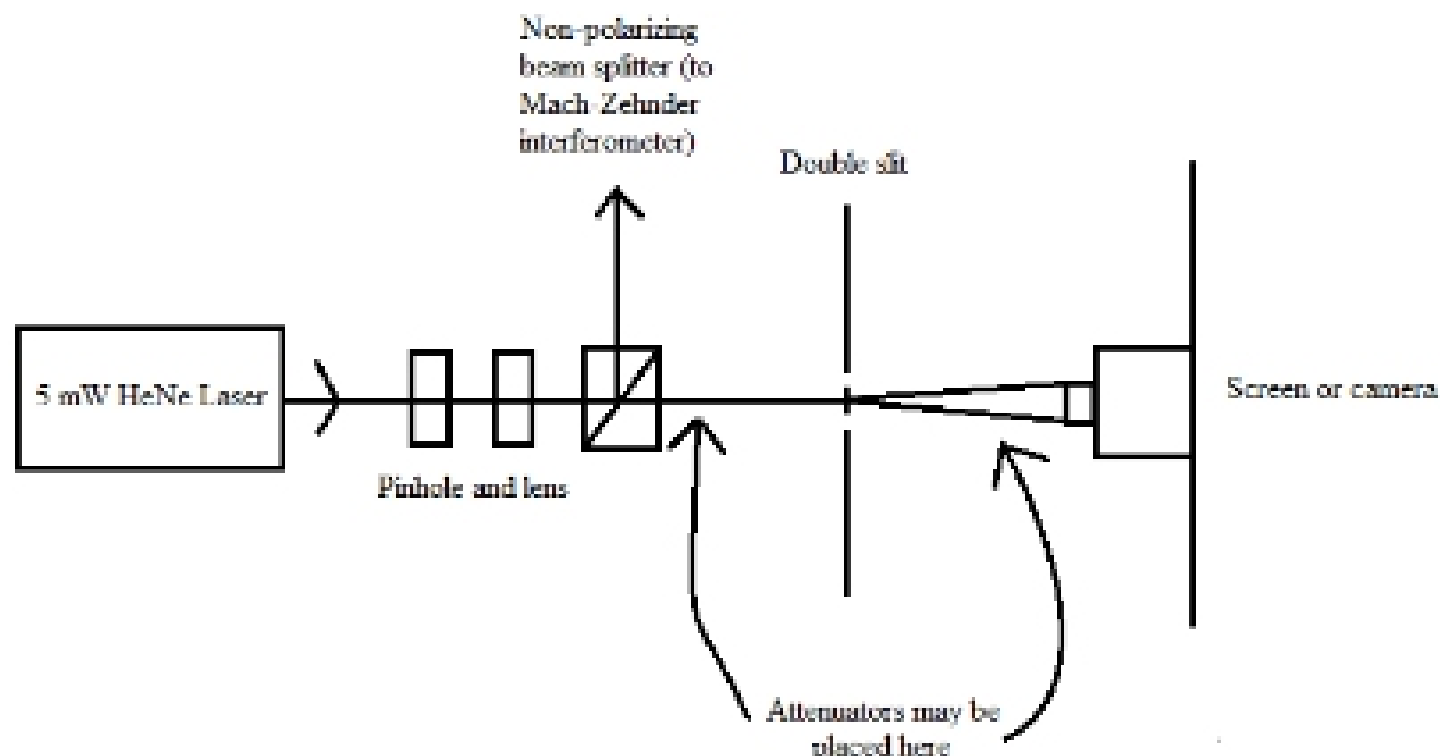
In modern times, Young's double slit experiment has become a useful demonstration of the wave-particle duality of light. With current technology, it is possible to create and image single photons. Thus, it is possible to perform the double slit experiment using a single photon. In this single photon variation, imaging will still detect fringe patterns, but they will be built up by multiple photon detections. Even though single photons pass through the slit, interference still occurs. This single photons apparently interferes with itself.

If single photons pass through the double slit apparatus, one might ask "Which slit does the photon pass through?" This question is apparently unanswerable. The act of observing which slit the photon passes through collapses the photons wave function, so that instead of being in a state of superposition between two interfering state, the photon will have a single definite state that cannot interfere with itself. Knowing which path the photon takes effectively removes the wave aspect of the photon's behavior, destroying any interference patterns.

The effects of this "which path" information can be seen in any variety of interference based apparatuses, apart from just the double slit experiment. For example, a Mach-Zehnder interferometer produces interference patterns by splitting a laser down two paths, and then recombining them. Difference in path lengths cause different phases between the two laser beams, leading to interference. If, however, one were to polarize the light along each path so that the light down one path were an orthogonal polarization to the other path, then which path light takes can be readily discerned by these differing polarization. In the process of introducing this which path information, however, the interference pattern will be destroyed. For any interference experiments, any way to discern the path a particle takes will destroy any interference patterns. In turn, if this "which path" information is somehow erased, the interference pattern can be recovered.

## 2 Experimental Setup

We made use of two separate apparatuses for this lab: the double slit apparatus and the Mach-Zehnder interferometer. Light was supplied to both of these setups from a 5 mW HeNe laser. The laser was collimated and a non-polarizing beam splitter divided the laser to both setups.



**Figure 2:** An outline of the double slit apparatus. Light is provided by a 5 mW HeNe laser, and collimated using a pinhole and lens. The light passes through the double slit, where the resulting interference pattern may be observed on a screen or imaged with a CCD camera. Attenuators could be placed on stands located both before and after the double slit. A beam splitter diverts some light to the Mach-Zehnder interferometer (which otherwise has no bearing on the double slit apparatus).

The double slit apparatus consisted simply of a double slit and attenuators (see figure 2). The double slit we used was made on a 2 millimeter thick piece of glass and had a slit width of 10 microns and a slit separation of 90 microns. A stand was fixed in front of and behind the double slit that allowed us to place multiple attenuators along the laser path. The laser beam passed through the attenuators and the double slit, where the output of the slit could be observed using a screen. The light out of each slit diffracts and interferes with the light from the other slit, resulting in a multi-fringed interference pattern. A CCD camera was used to image the resulting interference pattern, particularly when the beam was highly attenuated.

We placed enough attenuators along the beam path so that the rate of photons received by the CCD camera was quite low. It is worth noting that this does not constitute a single photon source. Even though the average spacing of the photons may be on the order of a meter, one would not be able to observe antibunching, as instead photons can form multi-photon bunches. Even though this is not the case of a single photon interfering with itself, the photon rate should still be sufficiently low to allow a basic demonstration of the particle nature of light.