# Single Photon Interference

**Physics 120 – General Physics I**

**Fall 2004**

## 1 Theoretical Background

In today's laboratory exercise you'll have a chance to perform experiments in which you can observe interference of single photons in a Mach-Zehnder interferometer. A schematic of this interferometer is shown in Fig. 1. In a way similar to the Michelson interferometer, the Mach-Zehnder interferometer has two paths for the light to follow. From a quantum mechanical perspective light is made of quanta called photons, and interference occurs because a photon can travel more than one path without an observer being able to tell which path the photon takes. Thus, at the heart of quantum interference in the *indistinguishability* of the paths.

In the case of Fig. 1, a photon can take either path 1 or path 2 in going from A to B. When the paths are indistinguishable we get interference. However, when we detect photons, which are indivisible, we record "clicks" in a detector. Thus, when there is constructive interference we get lots of clicks per unit time, and when there is destructive interference we detect a few or no clicks. Because quanta behave like particles at times and like waves at other times, constructive or destructive interference occurs due to the wave aspect of photons. That is, we get constructive interference when the difference in the lengths of the paths is a multiple of the wavelength of the light $\ell_1 - \ell_2 = n\lambda$, where $\ell_1$ and $\ell_2$ are the lengths of arms 1 and 2, respectively. Conversely, we get destructive interference when $\ell_1 - \ell_2 = m\lambda/2$ ($m =$ odd). If we smoothly change the length of one of the arms by slightly moving one of the mirrors, as shown in Fig. 1, we can smothly change from constructive to destructive interference. Experimentally we will record oscillations in the number of clicks as a function of the length of the arm.

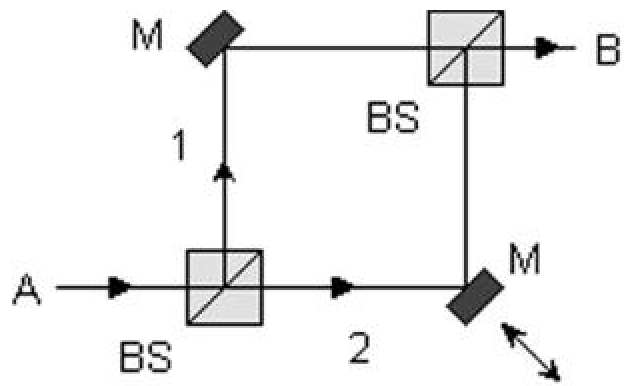


Figure 1: Schematic of a Mach-Zehnder interferometer.

In the laboratory we will use a more elaborate setup, shown in Fig. 2. The Mach-Zehnder interferometer is at about the center of the figure. However, it takes a lot of work to know that we have one photon of the proper wavelength going throught he interferometer so that we can distinguish the interference from a background of photons of different wavelengths. In order to know that we have the right photon going through the interferometer we "tag" it. A way to do this is to generate pairs of photons at the same time and then record clicks only when both photons hit corresponding detectors. The chance of accidental coincidences of unrelated photons is small.

To generate the pairs of photons we use a process called "parametric down conversion." In short, it is a process by which one photon of energy $E$ is absorbed by a material and regenerated in the form of two photons of energy $E/2$. The source of incident photons is a laser, and the pairs are produced in a crystal, which is the material that produces the down conversion. In Fig. 2 you can see the the paht of the incident photons leaving the laser, and going around to hit the crystal. After the crystal we have the down-converted photons going in different directions. We reroute the path one of them so that it goes through the interferometer and then to a detector. The other one goes directly to a detector. The detectors are very senstive to stray light so they are located inside light tight boxes. Light can only enter through two windows covered with filters.

In the lab today we collect data in three situations:

1. The first situation will be the single-photon interferometer. Here we scan the length of one of the arms of the interferometer while we record the number of photons reaching both detectors. If the paths are indistinguishable we should see interference. What do you predict?

   One of the arms has a half-wave plate (H in Fig. 2). This is a piece of optics that when set to a certain orientation it preserves the polarization of the light passing through it. In another orientation it rotates the polarization of the light. In this previous part the half-wave plate is set to preserve the polarization.

2. Then we use the single photon interferometer for the case when the half-wave plate in one of the arms is set to rotate the polarization of the photons traveling through that arm by 90. The polarization of the light entering the interferometer is vertical. The half-wave plate in the new setting will rotate the polarization of the photon to horizotal if it goes through that arm. If the photon goes through the other arm its polarization stays vertical. Thus, when the photon emerges from the interferomter it has the path information encoded in its polarization. However, we do not measure the polarization of the light after the interferometer. Do we see interference?

3. The final case is that of the single photon interferometer in which the polarization is rotated by 90 in one of the arms, as in the previous case , but with a polarizer with transmission axis at 45 placed

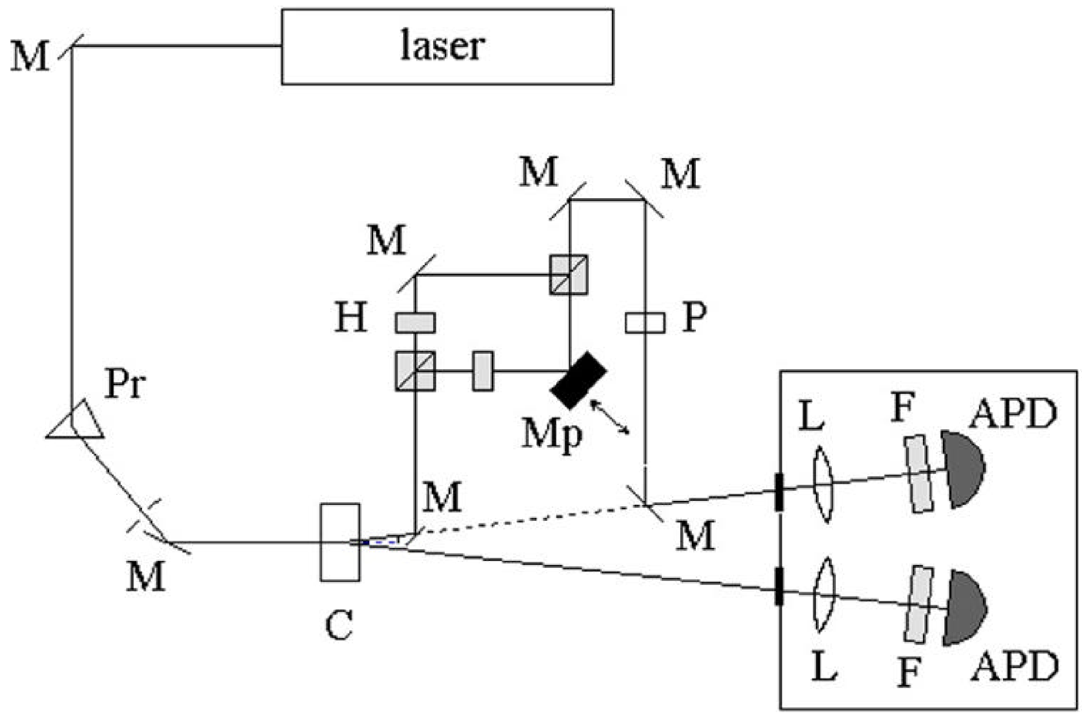


Figure 2: Diagram of the apparatus.

*after* the interferometer (P in Fig. 2). Some vertically polarized photons will pass through the polarizer and an equal amount of horizontally polarized photons will also pass throught the polarizer. After the polarizer the photons will be polarized along the transmission axis of the polarizer (i.e., forming 45 degrees with the horizontal). Do we see interference?

For each of these situations, you'll be given the data on a floppy disk, which you can take to the computers in Lathrop 211 to analyze. You may do the analysis as a group, but remember that the exam may contain questions about the lab.

# 2 Procedure

Each group member will have a task.

- Member 1 will be the operator of a program that takes data. We will take one data set. It will be divided into three sections corresponding to the three cases above. This operator must give a signal the other members to make the respective changes to the apparatus at the proper time.

- Member 2 will change the setting of the half-wave plate to one that rotates the polarization. This task is *very delicate* because a clumsy bump to any of the optical components will ruin the day. A misalignment will be a big setback, bringing infamy (not to mention loss of credit) to the perpetrator (and partners).

- Member 3 will place the polarizer in the correct place without bumping into anything else. Sounds easy? It must be done in absolute darkness! There is no room for human error.

## 3 Analysis

Your lab report will be fairly brief. It should contain:

1. Purpose
2. Diagram of the experimental apparatus. This should not be a drawing, but it should diagram the optical path and the important optical elements that are placed in the path. You should include the idler path, and you should give some idea of the size of the apparatus.
3. A brief procedure explaining how the apparatus was changed before each data set was acquired.
4. Plots of the coincidence data for the data sets, with the x-axis as the path length difference (calibrated). If the data are collected continuously, you may combine them in a single plot.
5. An explanation of why an interference pattern is observed or not observed in each situation.
6. A calculation in which you estimate the wavelength of the photons in the signal beam based on the distance between interference minima or maxima.
7. A calculation in which you estimate, on average, how many photons are in the interferometer at any one time. (Since this is an average, it does not need to be an integer.)
8. Conclusion, which will focus on the general rule that determines when we will or will not observe an interference pattern.

Information you may need to know:

- The wavelength of the incident blue laser is 457.9 nm.
- The piezoelectric that moves the mirror of the interferometer does not move linearly as a function of applied voltage. The calibration is as follows: $L = 1.546v(1 + 0.006v)$. In this equation, $v$ is the voltage signal recorded in your data file, and $L$ is the path length change in microns.
- The data file you are given contains both the photon counts of the APD in the idler beam, signal beam and also the coincidence counts between the signal beam and the idler beam.