**Morgan State University**

Quantum Laboratory Sequence

Quantum Lab #5: Single Photon Interference

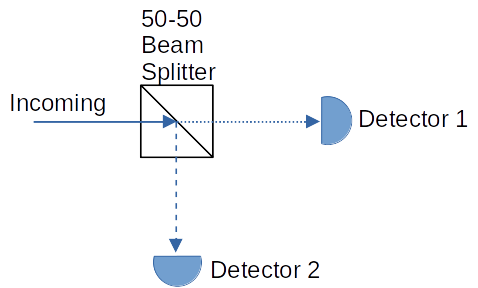
**Reference: Textbook Section**

**Motivation**

[For Eric]

**Background**

Classical light behaves differently from non-classical photons, in particular for single photons. As a classical example, consider light, whether from a thermal source or a laser beam, interacting with a 50:50 beam splitter (i.e. half the light is reflected and half is transmitted), as shown in Fig. 1. In this classical physics case, one would expect equal intensities at detectors 1 and 2, and indeed this is the result of such a setup. However, the result is completely different for the case of a single photon entering the beam splitter, since a single photon is a very quantum particle and will behave in an unexpected quantum manner.



**Figure 1.** Incoming classical light is split 50:50 into transmitted and reflected light received by detectors 1 and 2, respectively.

To better understand how a single photon will behave through a beam splitter, some quantum operator theory is helpful. Consider the four ports of a beam splitter as shown in Fig. 2. Let the quantum state be represented as a "ket" containing the number of photons. For example, port 1 with zero photons is represented as. Let the quantum annihilation operatorrepresent the loss of a photon. For example, assume port 1 has one incoming photon, represented as. The removal of this photon is done by operating on this state by , namely . Note that the subscripts should match to keep track of the operator on specific ports. To create a photon, we use the photon creation operator , which is the adjoint of . For example, to create another photon into port 1, the equation is, which shows that now port 1 has 2 photons entering it.

An amazing fact is that photons can be created out of the vacuum, and in fact this quantum vacuum is a necessary aspect of quantum mechanics, including the explanation for spontaneous emission. The equation to create a photon from the vacuum entering port 1, for example, is.

Now, let's investigate how a single photon entering a beam splitter will behave. To start, assume only vacuum at all ports, i.e. , , , and . Assume vacuum at port 0 and create a single photon entering port 1:

(1)

The effect of the beam splitter can be represented through creation operators through

(2)

Inserting Eq. (2) into Eq. (1) and operating on the output ports and results in

(3)

such that the resulting wave function representing the output of the beam splitter is

(4)

You may recognize Eq. (4) as being similar to the entangled state for horizontal and vertical polarizations, as reproduced below as Eq. 5.

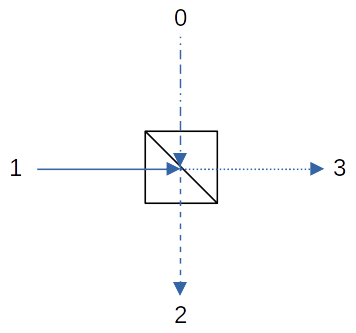
(5)

In fact, Eq. (4) represents an entangled state between the vacuum and a single photon produced at exit ports 2 and 3 as a result of the entry of a single photon at port 1 (and vacuum at port 0). The reality of Eq. (4) means that detectors placed at the exit ports 2 and 3 of the beam splitter will register a photon at either detector 2 *or* detector 3, but never at both simultaneously (i.e. no coincidence counts). In other words, the single photon entering port 1 will remain a single photon upon exiting the beam splitter, and thus behaves like a *particle*.

The probability that a photon will be detected at port 2 is given by bracketing Eq. (4) with thestate of a single photon in port 2, and taking the square

(6)

and similarly the probability of detecting the photon in port 3 is also 50%.

**Figure 2.** Illustration of a beam splitter with four ports labeled 1, 2, 3 and 4. Ports 0 and 1 are input ports and ports 2 and 3 are output ports.

**Experimental**

Now, what happens if we add another beam splitter, as shown in Fig. 3? The setup in Fig. 3 is called a Mach-Zehnder interferometer. Assume as before that vacuum is at port 0, and create a single photon entering port 1, denoted as, as the entry state into the Michelson interferometer. On the upper leg we add a phase shifter that adds a phase q on to the wave function for that arm. Now allow the photon number states emanating from the first beam splitter enter the second beam splitter have analogous ports 0', 1', 2' and 3'.

Using the same beam splitter creation operators as before, but for the inputs as indicated in Fig. 3 entering the second beam splitter. This results in the quantum state of the output ports 2' and 3' being

(7)

where *q*0 is an arbitrary phase. Equation (7) also represents an entangled state, but with oscillations. The probability of detecting a signal at port 2' or port 3' are similarly calculated as before, resulting in Eqs. (8). Thus, the probability of detecting a signal oscillates depending on the imparted phase shift *q*, indicative of the *interference of a wave* (the arbitrary phase *q*0 has been ignored).

(8a)

(8b)

As we have shown, a single photon entering a single beam splitter results in particle-like behavior of the emanating photon (i.e. a single photons exits one port or the other intact), but by adding another beam splitter to make an interferometer results in the photon behaving as a wave (i.e. the detector at either exit port will show oscillation fringes as *q* changes). This is the weirdness of quantum mechanics.

**Figure 3.** A Mach-Zehnder interferometer that causes single-photon interference at the output ports of the second beam splitter.

0

1

2

3

0’

1’

2’

3’



While a Mach-Zehnder interferometer was used above to illustrate single-photon interference, a Michelson interferometer provides the same effect, but by re-using the first beam splitter, as shown in Fig. 4. Since either port exit will contain the oscillating signal, just monitoring one port of the beam splitter (in this case port 0) will provide the oscillation data we desire.

**Figure 4.** Illustration of a Michelson interferometer where mirrors are used to reflect the outputs of the beam splitter back into the beam splitter, which has the same photon interference outcome as the Mach-Zehnder interferometer.

0

1

2

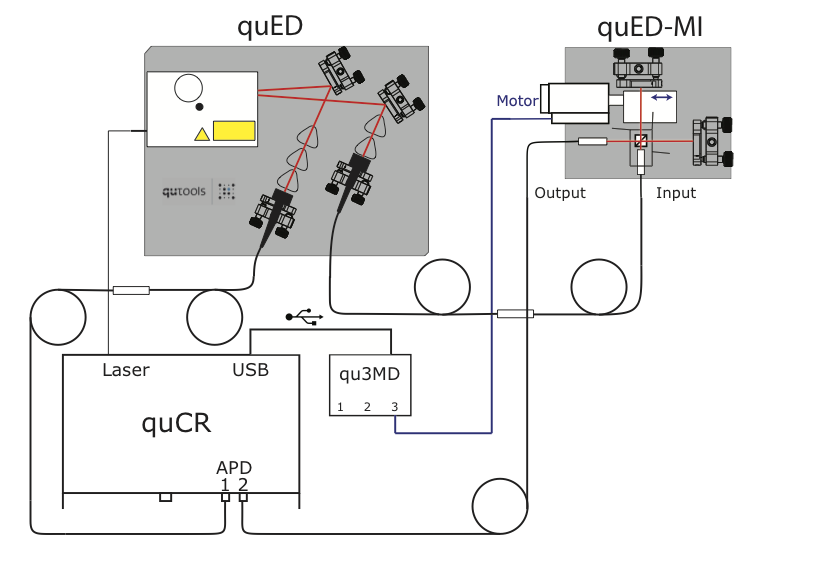
3

Mirror

Mirror

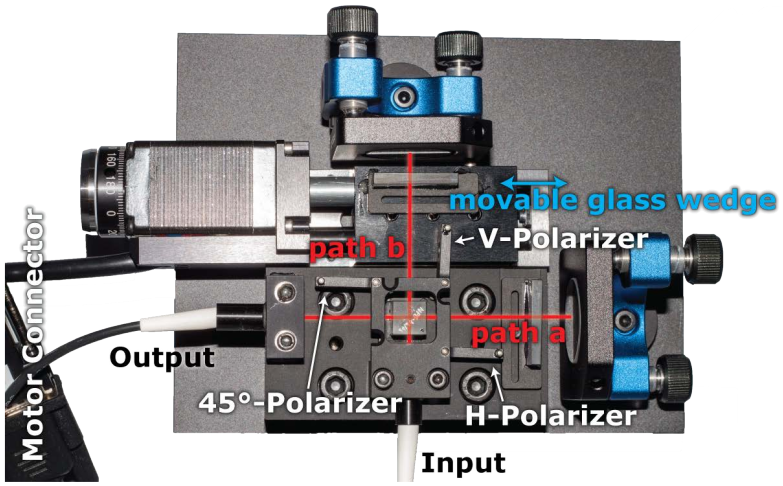
**Lab Setup**

A schematic view of the Michelson interferometer setup can be seen in Fig. 5. Note that single photon entangled pairs exit the quED section, with one being connected to APD 1 as a trigger signal for when to take a measurement, and the other photon heading to the quED-MI interferometer. The output from one port is used as the wave interference signal attached to APD 2. Thus the quCR records counts only when the Michelson photon signal arrives at the time triggered by APD 1.

**Figure 5.** The setup of the single photon experiment with all necessary connections.

**Realigning the mirrors**

Before the experiment is performed, the alignment of the mirrors in the interferometer should be checked. For that, block one path of the interferometer with a business card. Adjust the set-screws of the mirror mount in the open path to reach the count rate maximum. Repeat for the other path to reach approximately the same count rate in both arms.

**Figure 6.** The quED-MI AddOn Michelson Interferometer. The flaps with the polarizers are not used in this experiment and should be swung out of the beam path.

**Coarse interference searching**

The path lengths of the interferometer should be balanced when the movable glass wedge is aligned centrally in front of the mirror. To find out the actual position, a coarse search is helpful. Therefore, one can move the glass wedge over the middle position either manually by hand or using the quCR Tab quCNT linear scanning with the settings from Table 1. The Target has to be sepci#ed with the right sign (positive: the glass wedge moves away from the motor; negative: towards the motor). Interference can be observed on a distance of about 1, 5 mm (with the single photons from the quED), the maximal visibility occurs at balanced interferometer path lengths.

**Table 1.** The settings for coarse searching

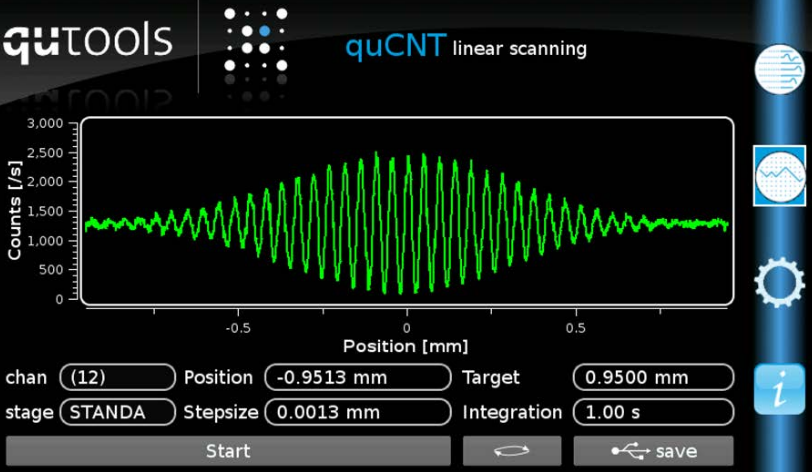
|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Channel | Stage | Step Size | Target | Integration Time |
| 12 | STANDA | 200/12,800 | ±6 mm | 0.1 sec |

**Measurements and Calculations**

To perform a good experimental run to record interference fringes, the integration time should be greater than 0.5 s. Also, the measurement points should lie closer together. Before the run, set the motor to a position away from the interference. The end of the measurement run is reached after a motor displacement of about 2 mm (Target=Position ±2 mm). The measurement example Fig. 7 was recorded with the values from Table 2.

**Table 2.** The settings for a good measurement run. Before the measurement, set the motor to a position away from the interference; the target is then accordingly chosen on the opposite side.

|  |  |  |  |
| --- | --- | --- | --- |
| Channel | Stage | Step Size | Integration Time |
| 12 | STANDA | 16/12,800 | 1 sec |

**Figure 7.** This measurement run was performed with the quED-MI Add-On in

a bright room on a conference table.

Once you are able to generate a fringe pattern like Fig. 7, save the data file.

**Discussion**