Lab 2. Single Photon Interference

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I. Abstract

Interference experiments are carried out at the single photon level in a Young’s double slit setup and a Mach-Zehnder interferometer. The dual wave-particle nature of photons is observed. The dependence of visibility of interference fringes on "which-path" information is also studied in the Mach-Zehnder interferometer.

II. Introduction

The principle of wave-particle duality stipulates that all matter has both wave and particle properties. The famous de Broglie hypothesis of 1924 was the first scientific generalization of this principle that related the momentum of a particle to its wavelength [1]. De Broglie’s principle states that all matter, be it a tennis ball or an atom, has a wave-like nature, with a wavelength described by the simple formula,

$$\lambda = \frac{h}{p}$$

where $p$ is the particle’s momentum and $h$ is Planck’s constant. The dual wave and particle nature of photons had been confirmed much before de Broglie’s hypothesis with Young’s double slit experiment that showed interference of two beams of light, and with Einstein’s hypothesis of the photoelectric effect and subsequent experiments. The question of duality was tackled by the Copenhagen interpretation of quantum mechanics, within which Bohr and Heisenberg proposed their famous complementarity principle. The complementarity principle stated that while matter had both wave and particle properties, an experiment could not measure both properties at the same time.

A problem arose when one tried to explain the wave nature of light at the single particle level. If a source of particles were to be attenuated so that only one particle at a time were to reach the slits in a Young’s experiment, then how could one conceive of the single particle giving rise to interference effects? The answer to this question was laid out quite clearly by Dirac. Within the Copenhagen interpretation, it
can be said that before photons are measured, they are described by their wave functions. Dirac postulated that wave function gives the probability of each photon being in a particular place and not the probable number of photons in that place, as was believed earlier [2]. Thus, when the wave function that describes a photon "approaches" two slits that are within a wavelength of each other, the probabilistic photon goes through both slits and essentially interferes with itself. While this is a strange concept to visualize, it is important to understand that within the Copenhagen interpretation of Quantum Mechanics, there is no deterministic reality before measurement, one can only describe the photon in terms of the wave function, which is probabilistic in nature.

Another way to understand the idea of a photon interfering with itself is in the Mach-Zehnder interferometer, which involves sending a photon through a beam splitter down two paths, and then varying one of the path lengths. According to Dirac’s interpretation [2], the photon probabilistically travels in both paths and hence can be said to be interfering with itself. Another way to explain this is that there is no "which-path" information available. If we try to measure which path the photon took, the probabilistic wave function that is present in both paths collapses to one of the paths and the interference effects disappear. It may be said then that the photon exists only after it is measured - though that idea is the subject of much philosophical debate.

III. Experimental Setup and Procedure

In our experiment, the single photons are generated by attenuating a CW HeNe laser at 632.9 µm to the extent that there is only one photon in the path at a time. This is done by measuring the laser power and dividing by the energy of a photon, which gives the number of photons per second coming out of the laser. Then, the time spent in the experimental setup is calculated by dividing the total path length by the speed of light. That time is then multiplied by the rate of photons to give the total number of photons in the experimental path at a time. The total attenuation required is simply the inverse of this number, which is experimentally obtained using neutral density filters of varying magnitudes. In the case of Young's double slit experiment, the attenuation required is calculated to be \(1.96 \times 10^{-5}\), which is obtained by grouping filter numbers 1, 1 OMA and 2 OMA together. In the case of the Mach-Zehnder interferometer, the attenuation required is calculated to be \(5.35 \times 10^{-6}\), which is obtained by grouping filter numbers 5, 1 OMA and 3 OMA together. In this manner, one photon at a time is obtained in the experimental path. A cooled EM-CCD camera is used to observe interference fringes.

In the case of the double slit experiment shown in figure 1, the acquisition time of the camera will be gradually decreased which corresponds to fewer and fewer single photons making it through the slits. This should result in a reduced visibility of interference fringes. It should also be possible to observe single events
that indicate discrete particle-like behavior of the photons by optimizing the gain and acquisition time. In the Mach-Zehnder interferometer, the light incident on the interferometer is linearly polarized at 45°. As shown in figure 2, the polarizing beam-splitter A then directs the 0° (H) component of the 45° photon into one arm and the 90° (V) component into the other arm. These orthogonal components meet at the second beam-splitter. A second polarizer D projects the output photon onto a new basis determined by the polarizer angle. If the resultant photon is then measured in the H or V basis, the "which-path" information of the photon is preserved and no interference is observed. If the measurement is carried out in the 45° or $(H - V)/\sqrt{2}$ basis, then the "which-path" information is erased. It can be said that the polarizer allows the 45° components of both the H and the V polarization states through, thus allowing interference to be observed.
If we were to explain this in terms of the Copenhagen interpretation, we would say that the wave function of the photon is actually in a superposition of all polarization states. A polarizer simply modifies the probability distribution to have a higher amplitude at the set polarizer angle. Hence for crossed polarizers, we get a $\sin^2 \theta$ dependence over time on relative polarizer angle $\theta$. The H and the V states in the Mach-Zehnder interferometer can be said to be in equal superpositions of $45^\circ$ and $-45^\circ$ states:

$$|H\rangle = \frac{1}{\sqrt{2}} (|+45^\circ\rangle + |-45^\circ\rangle)$$

$$|V\rangle = \frac{1}{\sqrt{2}} (|+45^\circ\rangle - |-45^\circ\rangle)$$

(2)

The polarizer at $45^\circ$ modifies both wave-functions to give a higher probability of $45^\circ$ states, and hence interference fringes are observed. As the polarizer is rotated to the H polarization basis, it modifies the wave-function of any incident photon to give a maximum probability amplitude for the H component and a minimum for the V component, thus making it impossible for the photon to probabilistically interfere with itself.

IV. Experimental Results

A. Young’s Double Slit Experiment

As is expected, the interference from the double slit setup reduces in visibility as the acquisition time is decreased and the gain is increased. For an optimal acquisition time and gain, one can clearly see the

![Figure 3: Particle-like behavior of single photons (image acquisition time 0.03 sec, gain=100)](image-url)
 particle nature of the photons as they make themselves manifest as discrete single events in figure 3. As is seen in figure 4, the interference fringes are washed out as the acquisition time is decreased from 1 second (with no gain) to 0.0003 seconds (with gain equal to 200).

B. Mach-Zehnder Interferometer

A similar experiment to observe particle-like behavior of the photons is carried out with the Mach-Zehnder interferometer. The acquisition time is slowly decreased and the fringes are seen to wash out. However, the more interesting experiment in this case is when the D polarizer is rotated from 45° to 90°. The fringe visibility is reduced, as is seen clearly in the CCD images in figure 5.
The fringe visibility for different polarizer D angles as seen along the vertical cross-section of the fringe images is also plotted in figure 6. The visibility reduction can be seen more quantitatively. This is not very precise as the fringes are not very uniform horizontally. However, on average, we can see that the visibility decreases. This confirms that the rotation of polarizer D erases the "which-path" information in the Mach-Zehnder interferometer and hence the clear fringes obtained at $45^\circ$ are washed out completely at $90^\circ$.

**VI. Discussion and Summary**

In this experiment, interference characteristics at the single photon level were studied. An attenuated CW laser was used to carry out Young’s double slit experiment with one photon at a time. Interference fringes were observed which washed out as the acquisition time of the image was decreased. Single events confirming
particle-like behavior of the photons were also observed. The Mach-Zehnder interferometer was used to carry out interference between single photons using two paths instead of two slits. A polarizer was used after the Mach-Zehnder interferometer to project the states onto the polarizer basis. This erased or preserved the "which-path" information and hence the visibility was seen to have a strong dependence on the measurement basis. Hence, interference was confirmed at the single photon level.

References: