LAB 4: Double Slit Diffraction of Single Photons

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Introduction

The end goal of this experiment is to demonstrate, as Richard Feynman said, the *only* mystery that is at the heart of quantum mechanics. For our purposes, that mystery will be defined as, "If a single particle is incident upon some choice in path and it is impossible to determine which path the particle took, then there will be wave like interference between the possible paths. But however if there is in principle some way to determine which path was traveled then there will be no interference." The single particles here will be individual photons and the choice in path is Young's double slit. The issue is the wave-particle duality of light, which apparently propagates as a wave, but is detected as particles.

The quantum nature of this experiment is ensured by the fact that the photons will pass individually though the slit and therefore it is not in the classical limit of a large number of photons. Despite the fact that single photons pass through each slit one at a time, you will find that the photons still create a standard Young's double slit interference pattern. You should review the classical Young's double slit experiment and the results to compare with what you see here

The basic experimental approach is to attenuate a light source incident on a double slit to such a degree so as to insure single photons pass through each slit – that is without having one photon in each slit simultaneously. The spatial variation in the position at which these photons strike a plane behind the slits is then recorded, and the double slit interference pattern is reproduced. Besides simply arguing the single photon nature of the experiment from the degree of light source attenuation, you will also demonstrate the quantized nature of light experimentally by using coincidence techniques to show that there is not a photon in each slit at any given time.

Apparatus

1. Light Source: The choice in light source was dictated by several requirements. First, a narrow enough frequency spectrum is needed such that the interference fringes will be easily resolved. Second, the wavelength of light needs to be easily detected with a reasonably high quantum efficiency. Lastly, as you will see, it is most straightforward to use a wavelength in the visible portion of the spectrum. One could use an incandescent light bulb (you might want to describe how this would be done after you have done this experiment) but the most straightforward approach is to use a laser. Our detector, discussed in the next section, will be a photomultiplier tube and for these the quantum efficiency increases as the photon wavelength decreases through the visible portion of the spectrum (why is this?). So the relatively inexpensive red HeNe laser is fine, but a green HeNe laser is even better. Your laser is a Coherent 31-2264-000 (serial No. 9726EF), a class IIIa laser with λ =543.3nm and power of 0.3mW with a random polarization (specifications in the Appendix).

2. Light Tight Box: As this experiment is about measuring single photons, light present from other sources, or scattered light from the laser itself, can introduce significant errors. Hence the

experiment is set up in a light tight box (Length = 36”, Width = 16”, Depth = 9”) see Fig. 1. As the PMTs dark current rises dramatically for 20 to 30 minutes following exposure to room light type intensities, both PMTs are enclosed in a secondary box as shown in Figure 1. This makes it possible to make certain changes to the apparatus without exposing the PMTs to room light. The box contains interlocks such that high voltage cannot be applied to the PMTs when either the 10^5 X attenuator (discussed below) is not in place, the box lid is not closed, or the inner PMT enclosure is not closed. In addition if not all of these conditions are met the electronic shutters on the inner PMT enclosure will not be open.

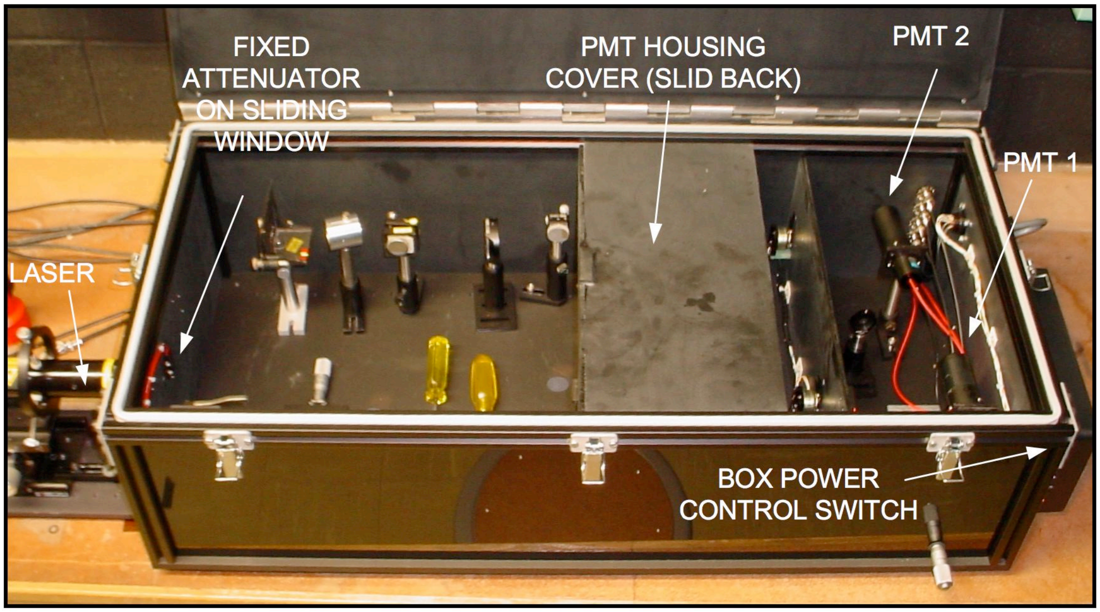

Figure 1. Photograph of the light tight box containing the experimental apparatus. A secondary light tight box encloses the 2 PMTs.

3. Photon Detector: The detectors used in this experiment are two Hamamatsu R1527 photomultiplier tubes (PMTs) (specifications in the Appendix). This photomultiplier was chosen its quantum efficiency at 543nm and its large signal to noise ratio. A high voltage source NO MORE NEGATIVE THAN -1200 V is applied to the PMTs. The size of the detector window on the PMT is a couple of centimeters in length however; the interference fringe measurement requires sub-millimeter spatial resolution. Therefore a single 50 μm entrance slit (in a 1" fixed lens mount) is placed in front of PMT 1 and both are mounted on a translation stage. This provides the required spatial resolution as the detector and entrance slit can be translated across the interference pattern while measuring the photon flux. Both PMTs have been enclosed in a secondary light tight box and in a magnetic shield, thereby limiting their field of view to background and scattered photons.

The PMTs are extremely sensitive to light (they count single photons). Normal room light intensities or the full power of the laser will destroy the PMT if it is on. Hence, the PMT is never to be turned on without the attenuation in place and the lid of the box closed!

4. Light Source Attenuation: To decrease the power of the laser beam to a level such that not more than one photon passes through each slit at a time, there is a series of 1/2" neutral density filters (attenuators) available (one at 10^1 X, one at 10^2 X, and one at 10^3 X). Fixed to the outside of the light tight box on a sliding window is an attenuator of 10^5 X. This prevents exposure of the PMT to excessive light levels. This 10^5 X attenuation level may or may not be enough to ensure a diffraction pattern produced by one photon at a time. You should calculate the required attenuation level and implement that level using the additional attenuators provided as discussed below.

5. The Double Slits: There are three sets of double slits used in this lab. One set is a double slit from Lennox Lasers. Those slits are 5.8 μm in width and separated by 228 μm. You should calculate the expected fringe spacing as a function of distance for this double slit geometry. The second and third set have slits with a spacing of ~ 1 mm in order to allow for integration of polarizers. One set of slits has no polarizers and the other set has polarizers installed behind each slit such that the light from one slit is polarized orthogonally to the light exiting the other slit.

Experimental Procedure

Arrange the apparatus such that you can see the double slit interference pattern using the Lennox Laser slits by opening the window in the box to remove the 10^5 X attenuator. Align the pattern such that it falls on the entrance window to PMT 1. It will be useful to align an antinode over the entrance slit. The quantum nature of this experiment is insured by the fact that the photons pass individually through the slit and therefore that it is not in the classical limit of a large number of photons. Hence you must now determine the degree of laser light intensity attenuation required to reach the single photon limit. This determination is made by a time of flight argument using the speed of light, the dimensions of the flight path in the light tight box, and the laser power. Other considerations may involve the aperture effect of the double slits. Insert appropriate additional attenuation, if needed, using the attenuator holder and attenuators supplied.

Seal the boxes, close the window and apply high voltage to PMT 1. Observe its output on the oscilloscope. Adjust the gain of PMT 1 until your signals are roughly 30 mV or possibly greater. Using the discriminator and scaler count the number of photons you see in a given time interval. Scan the entrance slit/PMT assembly horizontally using the micrometer while recording the number of counts you see as a function of position. Is the Young's double slit interference pattern observed? Are the number of counts you measure in a given time at a given point what you expect to see? What sort of error appears in any spatial pattern observed?

To verify your experiment is in the single photon regime, it is interesting to now investigate obtaining a single photoelectron pulse height spectrum from the PMT. How many incident photons does it take to create one photoelectron?

PMTs employ multiple stages in order to achieve the gains necessary for the signal to be visible by other instruments. In the first stage, the photoelectron produced at the photocathode strikes the first dynode, which produces some number, δ, of secondary electrons. These electrons then strike the second dynode, which in turn produces δ^2 electrons. This is repeated at each of the PMT's N dynodes so the final electron signal leaving the PMT is δ^N. In general δ increases as some power (>1) of the PMT voltage. There are statistical fluctuations in δ and in the simplest case on may assume these to be described by the Poisson distribution with a mean value of δ and a standard deviation of $1/\delta^{½}$.

What would the standard deviation be for 2 photoelectrons? What does this tell us about the distinguishing photon numbers as the number gets high? How would you expect δ to affect the spacing between energy levels? What is the photon energy of the green laser light? How much energy is needed to produce a single photoelectron? Two photoelectrons?

For a single photoelectron, the output of the PMT should be an energy distribution with a peak. How would the PMT output appear if one *and* two photoelectron events were present in the PMT. Operating under conditions you used for the producing the interference pattern with 'single' photons how does the output of the PMT appear if viewed using the MCA? Can you distinguish different peaks? If not try to increase or decrease the incident photon rate until you can see multiple peaks. Use this to calibrate your MCA. Which peak corresponds to what number of photoelectrons? of photons? Can you calculate δ for a given PMT voltage? Did you indeed accumulate your interference pattern with one photon at a time?

With the correct arrangement above we showed the quantum effect of single photon interference. Assuming light actually appears as discrete quanta of light (photons), we insured there was only one in the box at a time however we did not actually show that these the light quanta passed through only one slit at a time. If each light quantum passed through both slits then we would not need quantum mechanics to explain the phenomenon.

To prove that the light passed through only one slit at a time we'll divert the light passing through one slit to PMT 1 and the light passing through the other slit to PMT 2. To do this use the polarizing double slit (you may want to look at the interference pattern produced by these slits using the unpolarizing slit assembly). Put the polarized double slits in the light path such that the photon will first hit the double slit and then the polarizer. This way the polarizer has no way to influence the photons "decision" on how to pass the double slit. Use the fact that the beam is now polarized along with the mirror, polarizer, and glass slide supplied to guide the photons passing through each slit to the different PMTs as illustrated in Figure 2.

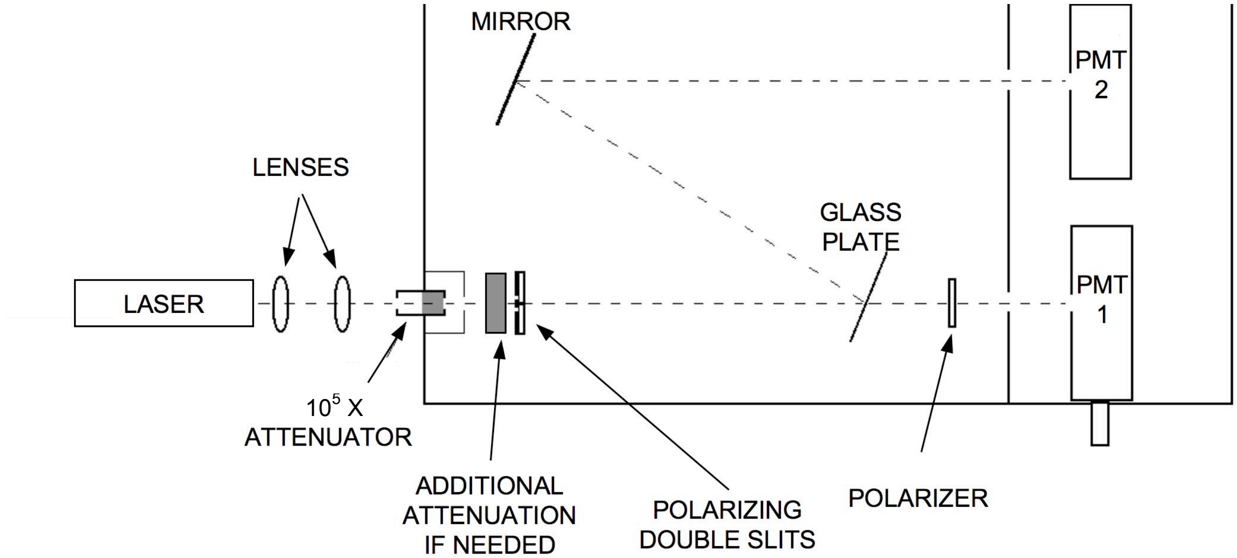

Figure 2. Schematic showing photon coincidence measurement

You may want to use a couple lenses to increase the diameter of the laser beam in order to better cover both slits of the double slit arrangement. How does one adjust the discriminator and coincidence to determine whether two photons pass through the two slits at the same time? Can one determine, on the average, how the time/distance separating the photons in the box from one another. If so, what distance do you estimate? What is the uncertainty in this measurement? Does the number of photons you observe in each detector agree with what you would predict? Does the fact that these slits are different from the slits you used previously impact your conclusions? How?

APPENDIX 1: Equipment Manuals

(Also refer to manuals associated with Experiment 2 on Nuclear Physics)