2-Slit Interference - One Photon at a Time

McCartney PHY334

Concepts

- Particle-Wave Duality; Slit Diffraction; Counting statistics; Photon-counting;

Background Reading

- Melissanos Ch5.2 (Young's Double Slit Experiment)
- TeachSpin 2-Slit Manual

Special Equipment

- Red laser (λ = 670±5 nm, 5mW); Green interference filter (λ = 546±5 nm)

Precautions

- A very sensitive photo multiplier tube (PMT) is used to detect single photons. The PMT will instantly die by exposure to "strong" light. With no high voltage (HV) applied to the tube, room-light is too much, with HV applied, star-light is too much. **Always** keep the photon shutter **closed** until ready for single-photon measurements. **Never** use it with the red laser, only with the green-filtered bulb with all apertures in place. Verify "shutter-down" before turning on any power to the unit.
- The light bulb source will last longer if not run at maximum power for extended times. Always turn it down before switching on/off.
- Do not allow the laser beam into the eye, either direct or by reflection.

Background:

This experiment provides an "in your face" encounter with particle-wave duality for photons. We replicate the historic "Young's 2-slit" experiment, using modern electronics that allows for detection of single photons. We measure the diffraction pattern for two slits, at a light level low enough that only one photon at a time is "in the box". So rather than the classical view of two plane waves interfering after going through the two slits we have, on average, only one photon in the box at a time. After some time and collecting many individual photons, we have a well defined interference pattern.

The apparatus consists of a long, thin light-tight box with two light sources (laser and thermal), 4 slit/aperture assemblies and two detectors: a photodiode for "strong " signals and a Photo-Multiplier Tube (PMT), for single-photon counting. You will first align the slits and apertures using the bright laser, which produces a visible Diffraction Pattern (DP) that you can see with your eyes to align the apertures and measure with a simple photo-diode. You then will swap-in the thermal source, with a narrow-band green filter, close the box, and measure the same DP acquired one photon at a time, using the PMT. The diffraction pattern is recorded in "serial readout" fashion by scanning a narrow slit across the pattern.

Theory for Diffraction Patterns

The theory for diffraction from slits was covered in PHY252, but here we will show that the interference pattern will be formed even when there is only one photon at a time in the box. Melisanos has a review you should familiarize yourself with.

1. ***Procedure: laser-pattern***

See the diagrams in the 2-Slit manual for an overview of the equipment

Set up the optical system for the laser diffraction measurement.

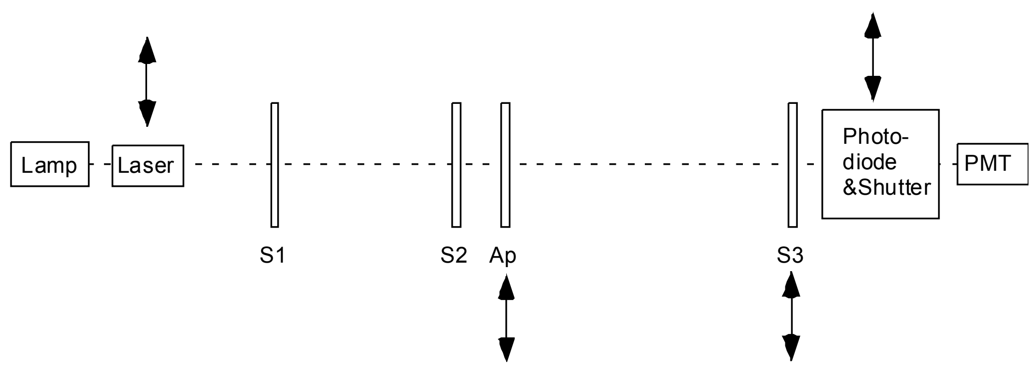

Fig. 2 Layout of light box.
S1= Fixed single-slit (unlabelled, width: a = 85 µm)
S2 = Fixed double-slit (width a = 85 µm, separation d = .014", .016" or .018"
**note these measurements are in "mils")*
AP= Moveable aperture to select slit A, slit B or both A&B
S3 = Moveable single-slit (a = 85 µm) to scan the diffraction pattern

a. Make sure the PMT HV is off and the photon shutter is closed (down).
b. Measure distances along the optic axis for sources and slits.
c. Open the box, slide the laser onto the optic axis and align it to the center of the detector window. Add the slits in "reverse order" (S3, AP, S2, S1) centering each on the optic axis. You only need do one slit size, S2 = .016". It will be useful and instructive to "see" the beam on a small white card at various locations along its path. The small red lamp may be useful to avoid dilation of your pupils. Take special care with the vertical orientation of S3 and S2 using the magnifier headset to get the 2-slit pattern parallel with the S3 slit. This affects the "sharpness" of tho scanned intensity pattern.
d. Place a view-card just behind AP, then find and record the micrometer settings that reliably pass slit A, slit B, both A&B or neither.
e. Place a view-card near S3 and sketch the DPs for each case: A, B, A&B. In particular, how does the intensity at a 2-slit max or min change in going to 1-slit? How can less light (change from 2- to 1-slit) give more signal? How can more light (change from 1- to 2-slit) give more signal?

2. Diffraction: and photodiode

a. With the box still open, connect a DVM to the preamp output. See that you can scan the DP by turning the S3 micrometer. Explore the useful range of motion. You should get something like 1 V at the center max of the 2-slit pattern, and <.05 V at the adjacent minimum (room lights off). The min value is particularly sensitive to good vertical alignment of S2 and S3.
b. Close the box so you can work with room lights on. Check for any light leakage into the box, and record a background "dark" value (detector thermal current).
c. Repeat the 1- vs 2-slit observations, this time with DVM values.

3. Data acquisition programs:
   a. Launch Desktop\2-slit diffraction.vi. This Labview Virtual Instrument (VI) will record the intensity reading at regular intervals set by "dwell time". Turn the S3 micrometer to collect the entire DP. When the STOP button is pressed, the VI will write the data file to Desktop/2-slit diffraction.xls. You must copy or rename this file (and close it!), before each "RUN", since it will be over-written. An efficient procedure is to copy from this file (then close it) into your user file, which you can leave open. The operator should turn the S3 micrometer at a steady rate. Record the starting and ending values of the S3 micrometer.
   b. Record DPs for slit A, slit B and slits A&B.
4. Diffraction: signal-photon counting
   a. With the laser 2-slit diffraction pattern aligned, shift S3 to the center max of 2-slit DP.
   b. Open the box and push the laser aside, without disturbing the slits. The optical alignment should remain "true" for the relatively broad beam from the green bulb. Close the box.
   c. (TA assist) Verify the setup for before opening the shutter of the PMT. With discriminator = 0.5 (1/2 turn), Gate = 1sec, Bulb = 0 but "on", gradually increase HV. You should begin to see (and hear) dark-counts near HV = 600. With HV = 600, set Bulb = 8, then slowly open the shutter. You should see Cts increase.
   d. Setting optimal HV: Working at 2-slit DP max, Bulb=8, Record counts vs HV, up to 800V. Set bulb= 0, and record "dark-current" at the same set of HV values. You should find a max in light/dark ratio, typically around 750V.
   e. Record a set of counts (maybe 10 values) at the DP max and adjacent min. Note the mean and the variance for each set of values. Which average number is better-defined (at DP max or min)?
   f. Measure counts vs Bulb setting, at the 2-slit max position.
   g. With Bulb = 8, find the 1- vs 2-slit max, min values (as in 4d above), this time with counts. Also get a reading for neither A,B. Why might this be different from "dark-current"?
   h. Use "2-slit diffraction-PMT.vi" to record scanned DPs for slit A, slit B and slits A&B.
5. Counting Statistics:
   We will study the counting statistics (mean, variance, standard deviation, outliers, etc) for a "single-value measurement" using a fixed slit position. Record a large set (N~ 10^3) of readings for statistical analysis for two cases: <Cts> ~ 100; <Cts> ~ 1. Choose diffraction settings and dwell as needed.

6. ***Data Analysis: Diffraction***

a. Compare your data against theory for the single-point (not scanned) values for 1- vs 2-slit max, min. You should subtract relevant backgrounds.
b. Fit your laser-DPs to theory to determine values for the 1-slit width, and the 2-slit width and spacing. If you do not have the entire width of the single slit pattern, estimate the fit using the given wavelength and slit width:

Single Slit:
$$I(\theta)=I_0\left[\frac{sin(\frac{\pi a}{\lambda}\sin\theta)}{\frac{\pi}{\lambda}\sin\theta}\right] \tag{1}$$

Double Slit:
$$I(\theta)=4I_0\cos^2\left(\frac{\pi d}{\lambda}\sin(\theta)\right)\left[\frac{sin(\frac{\pi a}{\lambda}\sin(\theta))}{\frac{\pi}{\lambda}\sin(\theta)}\right]^2 \tag{2}$$

where a = slit width, d = slit separation and the double-slit equation contains the effect of the single slits. See Melissanos equations #5.5 and #5.30.

i) Chop out "regions of interest (ROI)" and put them into New Cols.
ii) Shift the x-origin to the central max to save 1 fit param.
iii) Oscillating functions are tricky to handle, b/c they hang on local minima. Linearize trig functions, if appropriate. You must avoid closely coupled (or equivalent) parameters. Adjust "manual fits" until you are quite close. The plus/minus tweek buttons are useful for this. Auto-fit will converge if you are close.

c. Fit your single-photon 2-slit DP to theory (Eq 2), using your slit dimensions from the laser-data, to determine a value for the filter wavelength. Why are the minima here less deep than those for the laser DP?
d. (optional) From the laser DP, estimate the photon flux (# photons /sec) and compare with the laser spec of 5mW. Assume a beam diameter of 1mm at S1. The slits are 10mm tall. The photo-diode has sensitivity 0.4Amp/Watt, and the preamp has gain 22 x 10^6 Volt/Amp. The integrated flux in the central max of a 1-slit DP (Eqn 1) is 95% of the total flux.

7. ***Data Analysis: Counting Statistics***
a. For the high-count data (<C> ~ 100), make a scatter-plot, and "eyeball" the range that includes 68% of the points and the range that includes 95%. Compare these with the calculated σ and 2σ values. Are there any "outliers" in the scatter-plot?
b. For both high-count and low-count data, make a histogram of the count frequency, and compare with the calculated Poisson and Gaussian distributions.