PHYS 301 Lab Report: Single Photon

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1 Theoretical Prelude

Probability review:

The **Poisssonian Distribution** is a discrete probability distribution characterized by the mean λ. Suppose a positive random variable X follows a Poisssonian distribution. Then, the probability related to X is defined as follows.

$$\mathcal{P}(X = dk) \;=\; \frac{\lambda^k e^{-\lambda}}{k!} \tag{1.1}$$

It is straightforward to verify that indeed this distribution has a total probability of one and an expected value of λ.

A **Sup-Poisssonian Distribution** is a distribution with the same mean of a poissonian distribution, but a smaller variance than a poissonian distribution. In other words, any distribution where the variance is less than the mean is a Sub-Poisssonian distribution. Also, a **Super-Poissonian Distribution** is a distribution with variance greater than the mean.

Theoretical setup:

Light displays both the qualities of waves and particles. In this lab, we explore the wave nature of light. Suppose we pass a ray of laser through an interferometer. It is well known that the interferometer causes constructive and destructive interference assuming that the laser ray has sufficient intensity. According to the classical model, it is possible to interperet the interference as some statistical correlation; that is, the numerous photons interact in some complicated way to produce the interference pattern.

We challenge the notion that there exists a classical way to describe interference. Assume that the intensity of the light is small enough so that only a single photon passes through the interferometer in a small frame of time. According to the Classical model, since the single photon does not have another photon to interfere with, the probability of finding the photon must display a uniform distribution throughout the space of measurement.

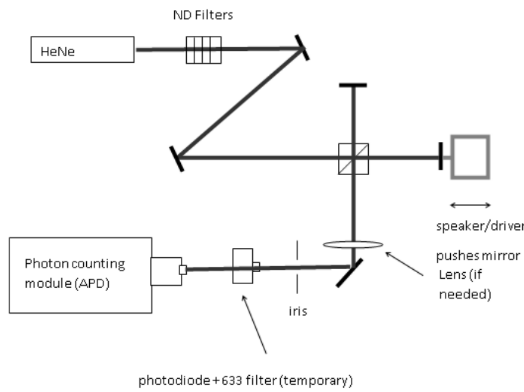
However, Quantum Mechanics claim that even a single photon displays a wave-like behavior, even in the absence of other photons. Therefore, if we observe an interference pattern for a single photon, we disprove the Classical Model and prove the Quantum Model.

2 Methods

Our experimental apparatus is comprised of the laser, Michelson Interferometer, and the detector. Our HeNe laser has 65W power, and emits a red laser with

3.2 Building the Michelson Interferometer

Your first goal is to build a Michelson interferometer:



a wavelength of $633nm$. The laser goes through the Michelson Interferometer, and the entangled ray is reflected to the detector.

We install a ND filter between the beam splitter of the interferometer and the laser to reduce the number of photons that engage in the interference. Also, an iris is installed in order to extract the laser intensity of a specific point in the interference pattern. In order to minimize the detection of black room photons i.e. the extraneous photons that exist within the dark room, we install a 633nm filter. The filter guarantees that the photons that hit the detector are solely from the HeNe laser.

One leg of the Michaelson Interferometer oscillates according to the voltage from the function generator. The voltage from the function generator is linked to the driver located at one end of the leg, leading the length of one end of the interferometer to change according to the function generator. By setting the function generator to send over triangular waves, we allow measurements of the photons to be made uniformly over the space.

From the NIM bin[1], we will use the Linear Gate. The Linear gate takes input from two terminals, the "Linear" terminal and "Gate" terminal. Whenever a pulse is detected from the "Gate" terminal, the linear gate outputs a pulse that has the magnitude of the Linear terminal.

By connecting the function generator to the "Linear" terminal and the photon detector to the "Gate" terminal, we can deduce the position of a certain photon. Our APD module gathers this data, and transmits to the MCA chanel analyser, which creates a historgram of photon counts for each voltage.

Contrast is represented as intensity of light, and is the outcome between the difference between light bright and dark fringes. Contrast diminishes as light intensity goes down and can be seen when comparing ND10(higher intensity) to

[1] NIM stands for Nuclear Instrumentation Module. It is a set of electronics built in the 1950's for nuclear and high energy physics.

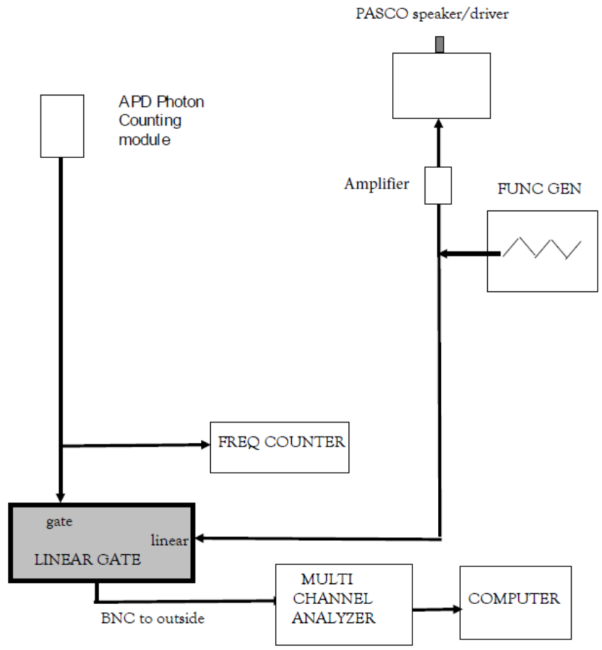


Figure 2: Electronics schematic for photon counting.
Technical Notes:
Linear Gate is Ortex #442. Linear gate signals must be positive, 0-10 V, with switch at GATED.

ND16(lower intensity).As fewer photons are able to interfere, the signal-to-noise ratio goes down, making the fringes less distinct. The sample data shows that although at ND 15 we can still see some contrast at ND16, the interference pattern becomes harder to detect and is likely due to the dark counts.

Contrast decreases as light intensity drops and can be seen by looking at higher ND filters. At ND15 and ND16, both low intensity, the contrast is lower than what can be seen with ND10 and ND11 filters. At ND 16, the photon count is so low that interference fringes are almost indistinguishable from background noise. By considering the contrast formula:

$$C = (I_{\text{max}} - I_{\text{min}})/I_{\text{max}} + I_{\text{min}}$$

We can see that the lower the value of I_{max}, due to less detectable photons, the bigger the impact of dark counts.

3 Experimental Data

Due to a small accident, our alignment was disabled after the measurement of ND10. Thus, we have supplemented our data from the previous measurements made by Professor Doret. The plotting of Professor Doret's data was done by a MATLAB script, written by ChatGPT.

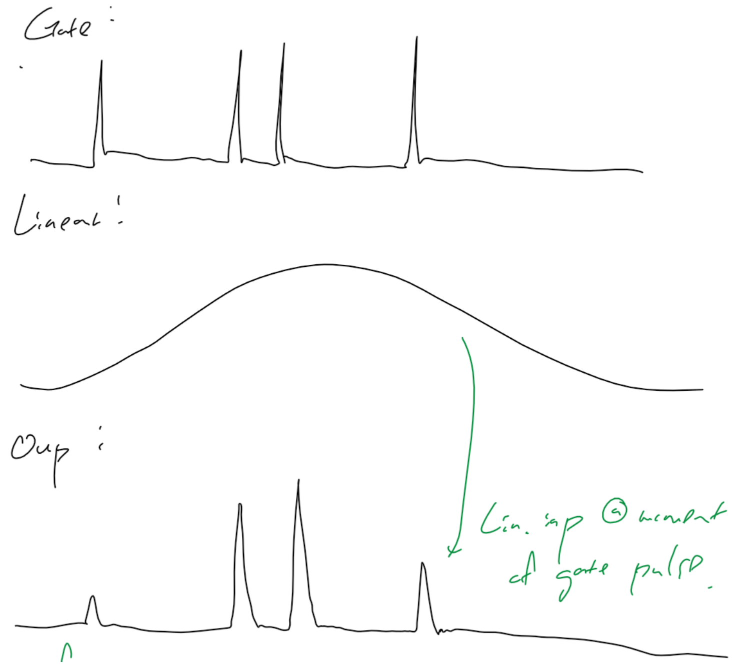


Figure 1: Output of the Linear Gate

We also present the data with normalization and a sinusioid fit. The parameters A, B, C, D specify the curve

$$A \sin(Bx + C) + D \tag{3.1}$$

4 Analysis

Filter necessary to observe single photon interference

In order to find out the domain in which the single photon interference happens, we first compute the necessary ND filter that allows the passage of a single photon per detection time.

The energy of a single photon is governed by the wavelength. We know that the HeNe laser has a wavelength of 633nm.

$$E_{ph} \;=\; \frac{hc}{\lambda} \;\approx\; 2.98 \cdot 10^{-19} \tag{4.1}$$

The sigle photon detector can make measurements up to the frequency of $f_d = 10^5 Hz$. Thus, if a single photon arrives at the detector for every time period $\tau \;=\; 1/f_d$, then the power received from the detector must be

$$P_d \;=\; E_{ph} f_d \;=\; 2.98 \cdot 10^{-14} W \tag{4.2}$$

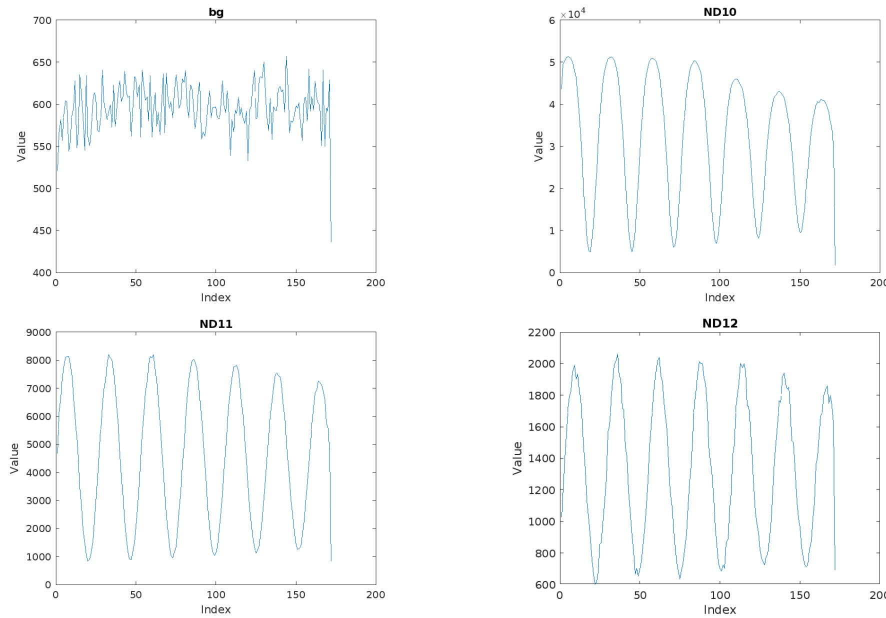


Figure 2: Raw Data: bg, ND10-ND12

Applying the ND 15 filter allows an appropriate power output up to a magnitude.

$$P_{\text{ND15}} = P_{\text{HeNe}} \cdot 10^{-15} = 65W \cdot 10^{-15} = 6.5 \cdot 10^{-14}W \tag{4.3}$$

So if we observe a sinusoidial distribution in our data for the ND15 or ND16 measurement, we have verified the wave nature of a single photon.

Using the χ-squared test, we verify that the fit for ND15, ND16 is indeed proper. According to a MATLAB computation, the χ-square value for the fit is 171 for both ND15, ND16. Given the degree of freedom of our fit is 168, we conclude that we have a good fit, and that we have observed single photon interference.

5 Error and Uncertainty

The photons follow a sub-poissonian statistic[2], assuming the quantum model. Therefore, the uncertainty of our measurement is around the square root of the

[2]In fact, it is also possible to verify the quantum model by using sub-poissonian statistics of the photon count. Instead of measuring the spacial distribution of the photons, measure the time-dependent distribution. According to the classical model, since the number of photons are always positive, the variance of the count must be greater than the mean. Nonetheless, in the quantum model, we can deduce that the variance can be less than the mean by the Common Commutator Relations of the anhilitors. So if the time-dependent distribution of the photon counts follow a sub-poissonian distribution, then the quantum model is verified.

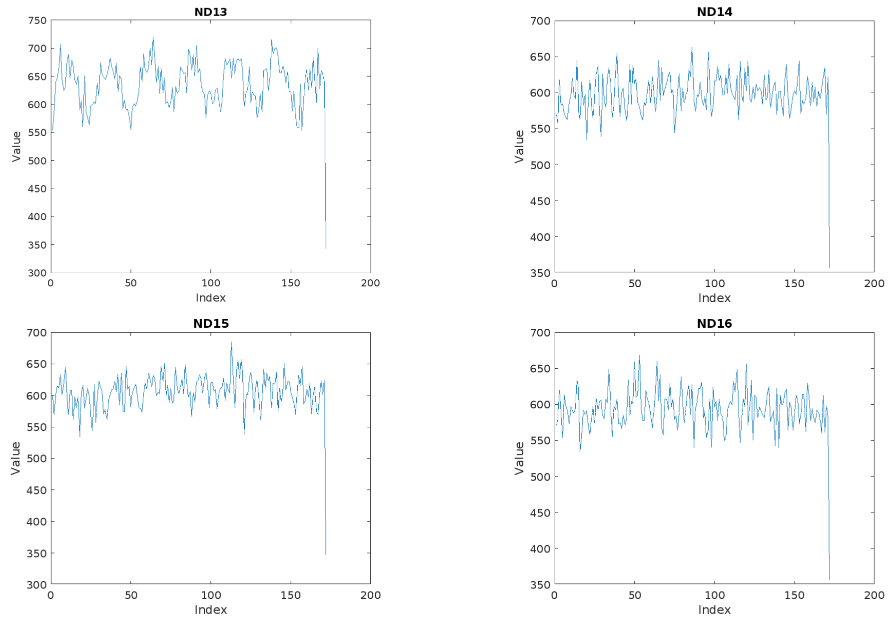


Figure 3: Raw Data: ND13-ND16

absolute measurement. For example, if our measured count at the voltage bin $4.95V$ $5V$ is 2500, then the uncertainty will be 50. Therefore we denote the count as 2500(50).

As for the measurements made in ND15 and ND16, the average count over all bins are around 600. Hence we assume an error of $\sqrt{600} \approx 24.5$. This about 2/3 of the amplitude of the fit value for ND15, and 1/2 of the amplitude of the fit value for ND16. Therefore, considering the uncertainty of the measurement, we deduce that our measuremnt is inconclusive, and we need more counts in order to pinpoint single photon interference.

ND Filters are the main source of loss in the beam path, but additionally other losses can come from the beam splitter, mirrors, and the APD detector. The APD's 70 % efficiency could have also contributed to loss.

6 Photon Count Rate and Spatial Distance Calculations

To calculate the spatial distance between photons in the interferometer, we use the photon count rate and the speed of light. The spatial distance between photons, D, is given by:

$$D = \frac{c}{C_R}$$

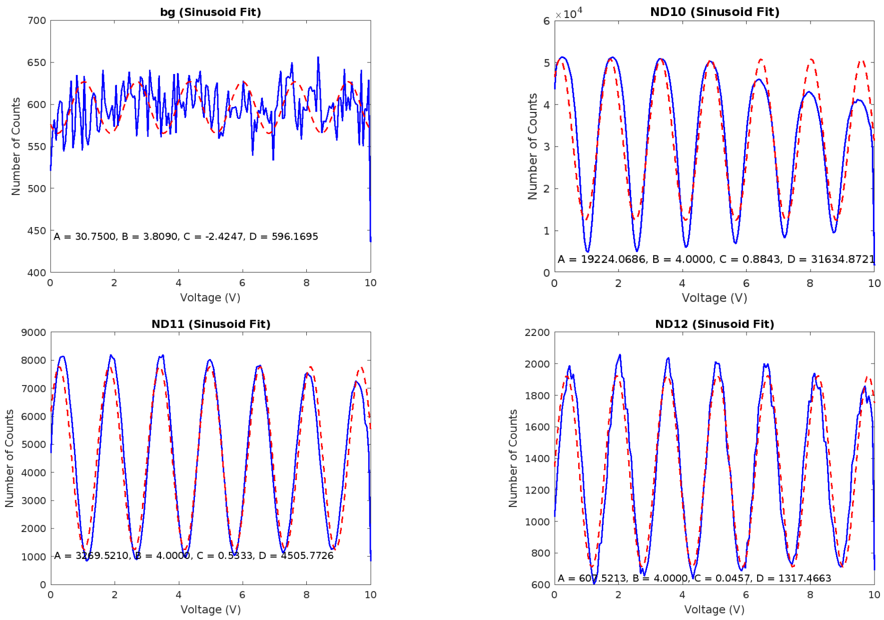


Figure 4: Sinusoid Fit: bg, ND10-ND12

where c is the speed of light (3×10^8 m/s) and C_R is the photon count rate. For a count rate of 800,000 photons/sec, the spatial distance between photons is:

$$D = \frac{3 \times 10^8\,\mathrm{m/s}}{800,000\,\mathrm{photons/sec}} = 375\,\mathrm{m}$$

Thus, the average spatial distance between photons is 375 meters.

6.1 Comparison of APD Count Rate to Predicted Photon Flux

We compare the total number of avalanche photodiode (APD) counts per second to the predicted number of photons based on the Neutral Density (ND) filters. The ND filters attenuate light by a factor proportional to $10^{-\mathrm{ND}}$. The predicted photon flux, N_{photons}, can be calculated as:

$$N_{\text{photons}} = \frac{P}{E_p}$$

where P is the laser power (10 mW) and E_p is the energy per photon (3.14×10^{-19} J). Substituting these values:

$$N_{\text{photons}} = \frac{10 \times 10^{-3}\,\mathrm{W}}{3.14 \times 10^{-19}\,\mathrm{J}} = 3.18 \times 10^{16}\,\mathrm{photons/sec}$$

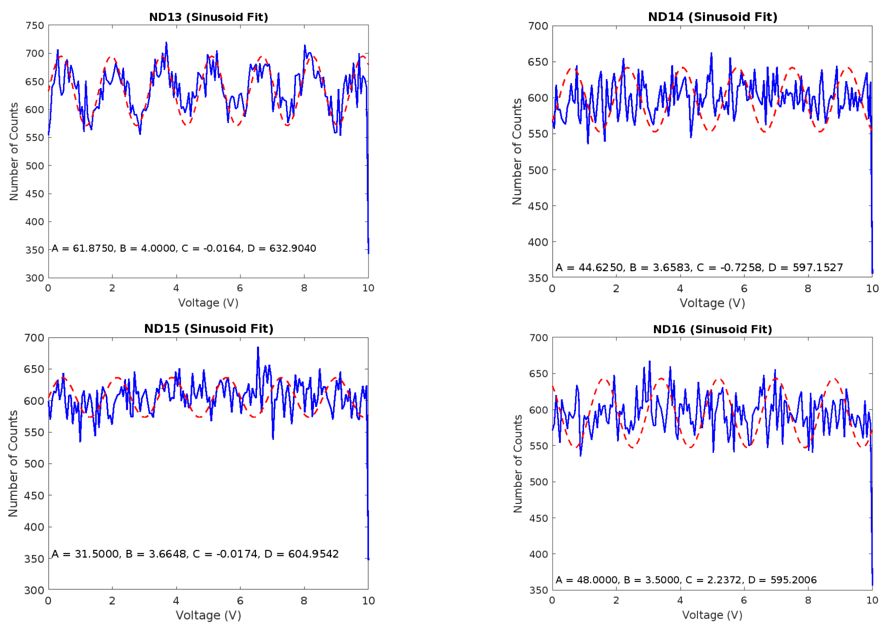


Figure 5: Sinusoid Fit: ND13-ND16

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Fitted parameters for ND15: A = 31.5, B = 3.6648, C = -0.017359, D = 604.9542
Chi-square statistic = 171, Degrees of Freedom = 168
Fitted parameters for ND16: A = 48, B = 3.5, C = 2.2372, D = 595.2006
Chi-square statistic = 171, Degrees of Freedom = 168
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Figure 6: χ-squared test results

Thus, the source emits approximately 3.18×10^{16} photons per second.

For a measured photon count rate of 800,000 photons/sec with an ND8 filter, we calculate the attenuation factor:

$$A = \frac{N_{\text{initial}}}{N_{\text{final}}} = \frac{3.18 \times 10^{16}\,\text{photons/sec}}{800,000\,\text{photons/sec}} = 3.18 \times 10^{11}$$

6.2 Accounting for APD Efficiency

The APD detector's efficiency is 70%, so the actual photon count rate is:

$$C_{\text{actual}} = \frac{C_{\text{measured}}}{\eta}$$

where C_{measured} is the measured count rate and $\eta = 0.70$. Substituting the values:

$$C_{\text{actual}} = \frac{800,000}{0.70} = 1,142,857\,\text{photons/sec}$$

6.3 Error Propagation

To account for uncertainties in the measured count rate and the detector efficiency, we calculate the relative uncertainty in the actual count rate using the formula:

$$\frac{\Delta C_{\text{actual}}}{C_{\text{actual}}} = \frac{\Delta C_{\text{measured}}}{C_{\text{measured}}} + \frac{\Delta \eta}{\eta}$$

The statistical uncertainty in the measured photon count rate is:

$$\Delta C_{\text{measured}} = \sqrt{C_{\text{measured}}} = \sqrt{800,000} = 894.43$$

The relative uncertainty in the measured count rate is:

$$\frac{\Delta C_{\text{measured}}}{C_{\text{measured}}} = \frac{894.43}{800,000} = 0.00112\,\text{or}\,0.112\%$$

The relative uncertainty in the detector efficiency is:

$$\frac{\Delta \eta}{\eta} = \frac{0.01}{0.70} = 0.0143\,\text{or}\,1.43\%$$

Thus, the total relative uncertainty in the actual count rate is:

$$\frac{\Delta C_{\text{actual}}}{C_{\text{actual}}} = 0.00112 + 0.0143 = 0.01542$$

The total uncertainty in the actual count rate is:

$$\Delta C_{\text{actual}} = 0.01542 \times 1,142,857 = 17,616\,\text{photons/sec}$$

Thus, the final photon count rate, accounting for uncertainty, is:

$$C_{\text{actual}} = 1,142,857 \pm 17,616\,\text{photons/sec}$$

6.4 Analysis

The APD detector's efficiency significantly affects the photon count rate measurements. Since the detector is only 70% efficient, the actual photon count rate is higher than the measured rate. The combined uncertainties from photon counting statistics and detector efficiency increase the overall error in the photon count rate. This effect becomes more pronounced at higher ND levels, where the photon count is lower and the impact of background noise and detector efficiency uncertainty is greater.

7 Conclusion

The objective of this experiment was to observe single-photon interference using a HeNe laser, Neutral Density (ND) filters, an ultra-sensitive avalanche photodiode (APD) detector, and a multi-channel analyzer to collect and analyze the resulting interference patterns. Although we were unable to use our own collected data, the provided sample data clearly demonstrated how increasing the attenuation (by adding ND filters) affected the interference pattern. As the light intensity decreased, especially at higher ND levels like ND15 and ND16, the contrast of the interference fringes became less distinct. This is expected, as higher attenuation leads to lower photon counts, making it more difficult to distinguish actual photon signals from background noise. Despite the lower photon count at ND16, we were still able to fit a sinusoidal curve to the data, confirming the presence of an interference pattern. This outcome supports the quantum mechanical prediction that even at low intensities, photons can interfere with themselves, demonstrating wave-particle duality. The experiment ultimately reinforced the concept that even with fewer photons, the quantum nature of light persists, allowing us to observe interference, albeit with reduced clarity at higher ND levels.