Single and Double-slit Interference with a Laser and One Photon at a Time

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The purpose of this experiment is to observe wave-particle behavior and test Fraunhofer diffraction theory when multiple photons and individual photons pass through both single and double-slits. Two separate light sources are used: a laser and a green-filtered lightbulb; aligned so that photons which are emitted may travel through varying slit orientations into a photodiode and a photomultiplier tube both in groups and individually, respectively. We find that when observed, light in both cases creates interference patterns; implying that individual photons are interfering with themselves.

Introduction

In 1801, Thomas Young designed an experiment that stood to adjudicate Isaac Newton's theory that light was a particle. In conducting this experiment, he found that light created an interference pattern when passing through two adjacent slits: wave-like behavior. This was accepted until Einstein's research into the photoelectric effect showed that light can behave as a discrete packet of energy when colliding with an electron. These two contradicting results imply the existence of a wave-particle duality. At the heart of quantum mechanics lies the phenomenon of quantum superposition, where a system can exist in differing configurations simultaneously, a photon passing through both slits simultaneously in this case.

In this experiment we observe photons traveling in groups and individually through single and double-slits, using a laser and a green-filtered lightbulb respectively as seen in **Fig. 1**. Using a photodiode which creates current proportional to light intensity, we gather data on the interference patterns through single and double-slits through a voltage-output signal as a function of the detector slit position. Then using the lightbulb, we use the principles of the photoelectric effect through a photomultiplier-tube (PMT) to detect individual photons and gather data on their counts over a fixed time as a function of the detector slit position. In reconducting Thomas Young's Double-slit Experiment, we find that even when individual photons behave as particles in accordance with the photoelectric effect, they are observed to accumulate into interference patterns consistent with Fraunhofer theory, indicating that they are traveling through both slits simultaneously and are interfering with themselves.

Theory

There are two ways in which we may observe light; wave-like and particle-like. If it is wave-like, we can expect that the waveforms passing through each slit will interfere with one another and create an interference pattern across the detector that can be modeled with Fraunhofer's diffraction theory, as seen in **Fig. 2**. If it is particle-like, we can surmise that they will create two independent bands respective to the slit they passed through.

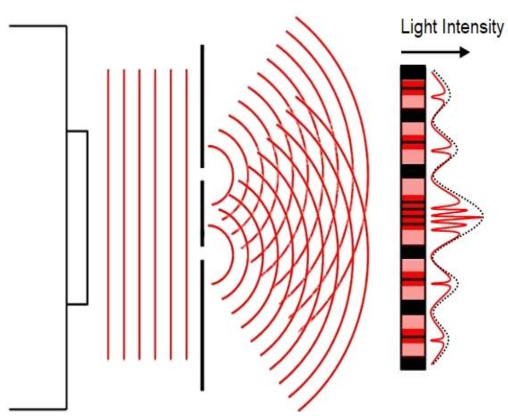


Figure 2: Wave-like double-slit diffraction pattern

The interference patterns can be modeled using Fraunhofer's diffraction equation for diffraction, which gives the intensity of the light at an angle (θ) with respect to the horizontal plane as seen in **Fig. 3**. The intensity equations for a double-slit (equation 1) and single-slit (equation 2) are as follows[1]:

$$I = 4I_0\left[\frac{\sin\left(\frac{\pi a \sin(\theta)}{\lambda}\right)}{\frac{\pi b \sin(\theta)}{\lambda}}\right]^2 \cos^2\left(\frac{\pi b \sin(\theta)}{\lambda}\right) \qquad (1)$$

$$I = I_0\left[\frac{\sin\left(\frac{\pi b}{\lambda}\sin(\theta)\right)}{\frac{\pi b}{\lambda}\sin(\theta)}\right]^2 \qquad (2)$$

Where b is the slit-width, a is the slit-separation, λ is the wavelength of the light, and I_0 is the initial intensity.

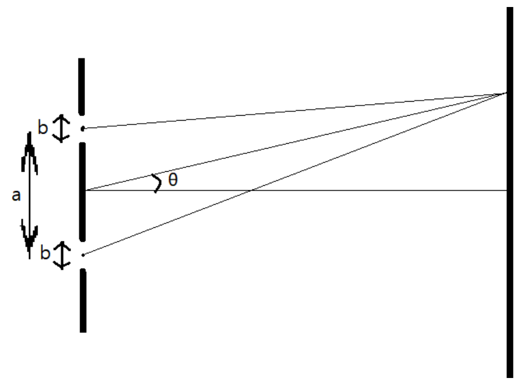


Figure 3: Fraunhofer diffraction theory for a double-slit

Finally, when the photons are limited to one at a time, a PMT will be used in order to convert the individual photons into current which can be measured. The PMT utilizes the photoelectric effect which is a process in which electrons are emitted from a photosensitive material when exposed to electromagnetic radiation. From a classical framework, if the photons were to act as waves, it would take a period of time for the electrons to absorb their energy until they reach some threshold and eject. Instead, the electron is ejected immediately upon collision with the photon, indicating that the photon is behaving as a particle. Therefore, when measuring single photon counts, we can be confident they are acting in a particle-like manner.

Experimental Methods

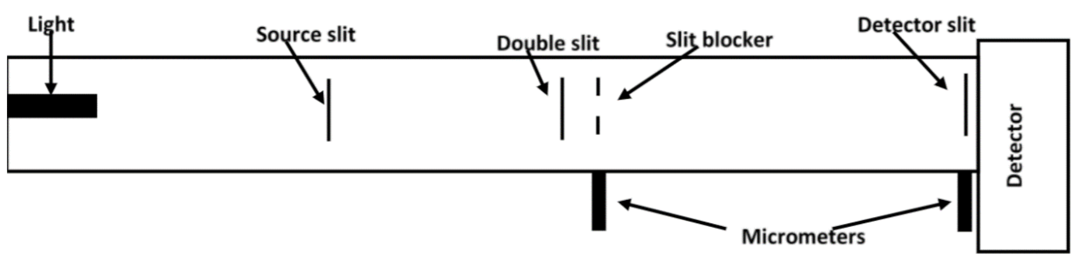


Figure 1: Experimental Apparatus

The experimental apparatus is seen in **Fig. 1**; it is a long-closed box which allows for light from either a laser or a lightbulb to pass through a source slit towards a double-slit, measurements of which can be found in **Appx. A**. The position of the slit blocker allows for both single-slit (left-slit open or right-slit open) and double-slit configurations, which is adjustable with its respective micrometer. The light which passes through the double-slit is then met by a detector slit, which allows light to pass through a controlled point which can be swept across the detector with its respective micrometer in order to take data as a function of position.

To begin, a qualitative observation of interference patterns is made with a laser whose light is passed through single and double-slit orientations projected onto a piece of paper in front of the detector slit. This allows for observation of the interference patterns as well as alignment of the laser in relation to the slits so that we may record and measure their ideal positions for further experimentation. After this, the paper in front of the detector slit is removed and the box is closed to eliminate contamination of ambient light. The detector's photodiode outputs voltage signals to a multimeter and its amplitude is recorded as a function of the detector slit position by adjusting its respective micrometer. The data obtained for the single-slits (left-slit open and right-slit open, summed) and the double-slit is then fitted to Fraunhofer theory to test if it is consistent with wave-like behavior.

Finally, the laser is replaced with a low intensity green-filtered light bulb which passes light of a wavelength between 541-551nm, the photodiode in the detector is replaced with a PMT, and a photon counter is connected to the PMT output. A separate procedure is conducted to determine the proper discriminator settings in order optimize captured data for single photons. This is done by taking both light and dark counts (when the PMT is exposed and covered, respectively) across a range of voltage biases using fixed a photon-counter discrimination, then finding where the discrepancy between the two trends is greatest. Once the ideal discriminator setting is found, the number of relative photon counts is recorded over a 10 second interval as a function of detector-slit position for single and double-slit orientations and the data is compared to Fraunhofer theory and the results of the laser data.

Results

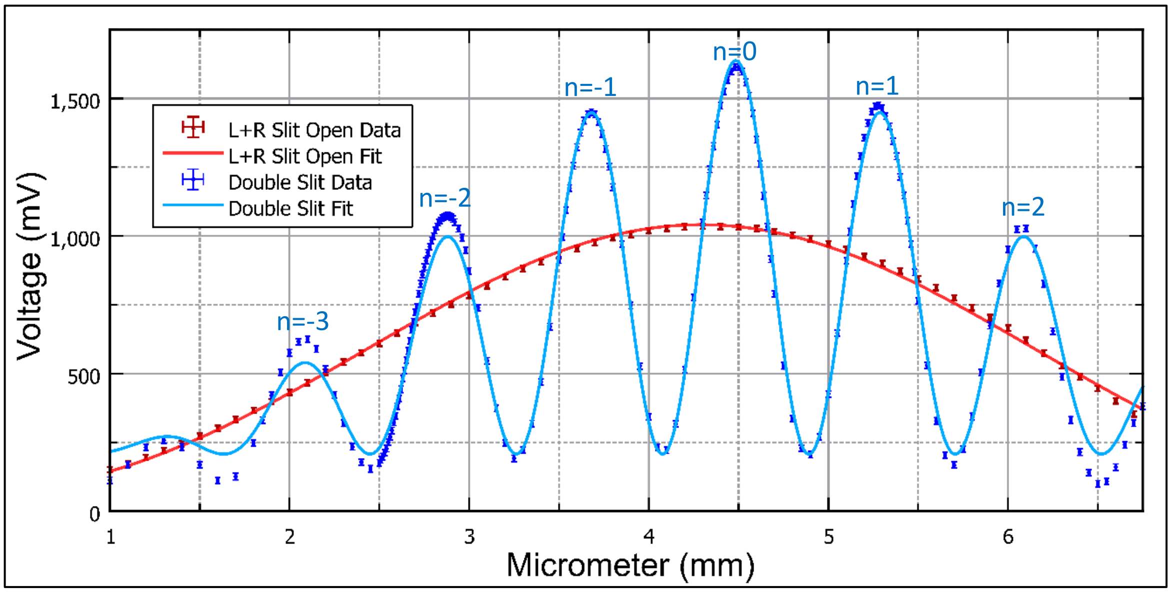


Figure 4: Output Voltage as a function of micrometer position for double-slit and L+R slit open with a laser, fitted to equations (1) and (2) respectively. *The interference patterns seen were obtained using a laser with an output wavelength of 670 ± 5nm and an output power of approximately 5mW, according to the manufacturer[2].*

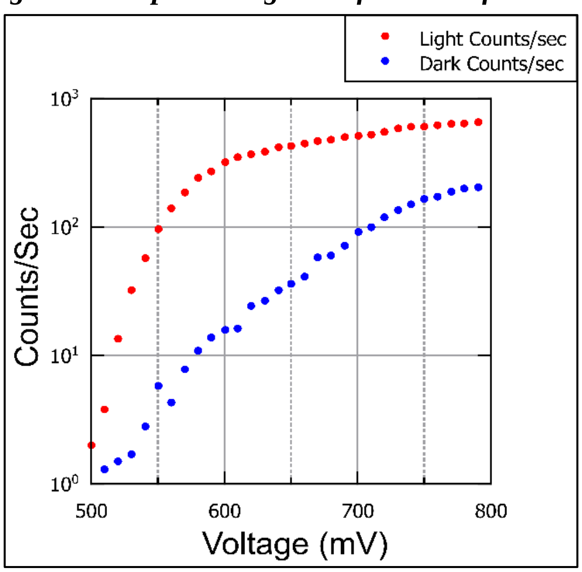


Figure 5: Light and dark counts as a function of PMT voltage bias with a fixed discriminator value of 0.2

In order to ensure only one photon at a time is passing through the slits, optimizations were made. A plot of both light counts (when the PMT shutter is up) and dark counts (when the PMT shutter is engaged) were taken as a function of the PMT voltage bias with a fixed discriminator value of 0.2, as seen in **Fig. 5**. From this, a voltage bias of 650mV was chosen for the lightbulb, as it provided both a stable value in terms of light-counts, and a large discretion from the dark count noise. A plot of light and dark counts as a function of discriminator settings with the previously found voltage bias of 650mV can be found in **Appx.**

B. The PMT output and the photon counter output were connected to separate channels on an oscilloscope to trigger upon individual counts.

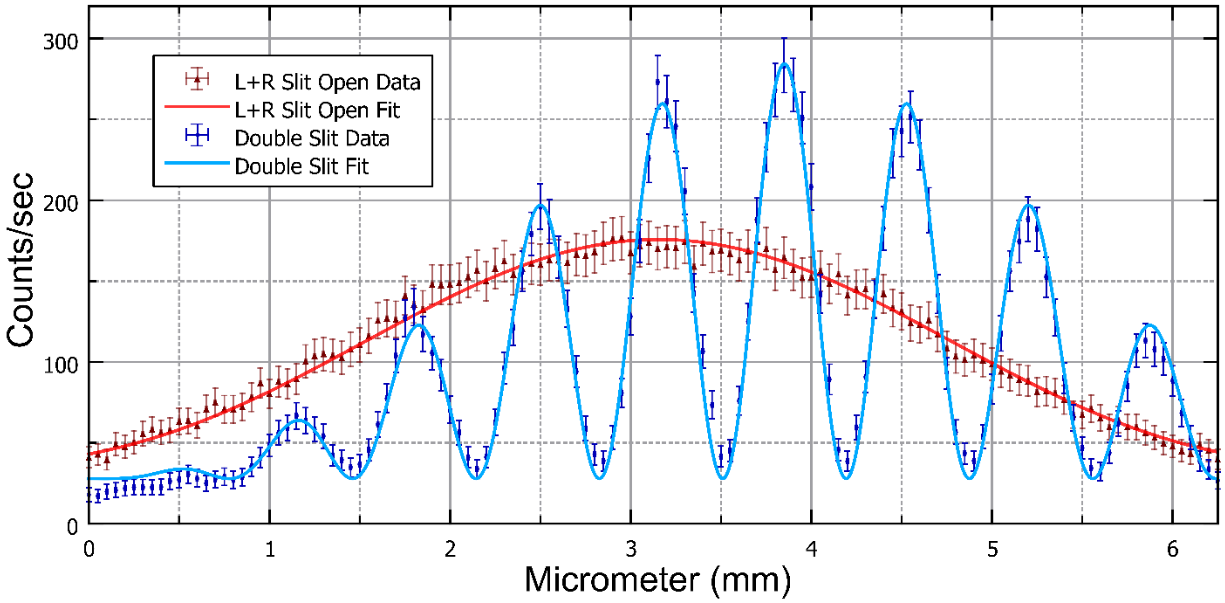


Figure 6: Photon counts per second as a function of micrometer position for double-slit and L+R slit open, fitted to equations (1) and (2) respectively.

The largest source of error in taking data for the laser configuration was that of voltage noise. We measured that when the box was closed and the laser was off, there was an ambient voltage noise of 11.4mV. As for the detector slit position, the micrometer could only take measurements to an accuracy of 0.01mm, therefore we assigned an error of ±0.005mm. When taking data for one photon at a time, we were relying on counts of photons over time, which is a measurement of discrete random events. Therefore, we assigned the error of each count to be the Poisson distribution $\pm\sqrt{n}$, where n is the number of counts.

For the calculations of slit-width and slit-separation, the errors of fitting parameters *a* and *b*, were propagated along with the error in laser/lightbulb wavelength provided by the manufacturer, and the error in the distance measurement from the double-slit to the detector. This error was determined to be ±0.005mm. A table of calculations of slit-width, slit-separation, and the reduced chi-squared of each fit can be seen in **Fig. 7**.

	Slit Width	**Slit Separation**	**Reduced Chi^2**
L+R Slit Laser	0.067±0.005mm	-	12
Double-slit Laser	0.077±0.005mm	0.037±0.005mm	0.96
L+R Slit Lightbulb	0.077±0.005mm	-	0.21
Double-slit Lightbulb	0.078±0.005mm	0.044±0.005mm	0.99

Figure 7: Slit-width, slit-separation, and reduced chi squared for all experimental configurations.

Discussion and Conclusion

The interference patterns for both single and double-slits were observed on a piece of paper in front of the detector slit and were consistent with what was expected of wave-like behavior. This was further confirmed when the paper was removed and the light was able to hit the detector, allowing for measurement of the intensity from the photodiode as a function of detector slit position. The results can be seen in **Fig. 4**, where the interference patterns made with the summed single-slits and the double-slit are fitted to Fraunhofer theory. The fitting of the interference patterns with their respective Fraunhofer models yields a reduced chi-square of 12 for the double-slit fitted to equation (1), and 0.96 for the added single-slits fitted to equation (2). The reduced chi-squared of the double-slit data is quite large indicating that there was likely a source of error we did not account for. In addition to this, it is clear that the Fraunhofer fit does not perfectly align to the outer fringes of the double-slit data as seen to the left of $n = -2$ and the right of $n = 2$ in **Fig. 4**; despite this, it accurately matches the height and widths of the 3 central fringes: $n = -1, 0, 1$. Overall, both data sets are consistent with wave-like patterns as described by Fraunhofer theory.

When the light is reduced to one photon at a time, the resulting photon counts as a function of detector slit position yields interference patterns similar to the laser data as seen in **Fig. 6**. Fitting the double-slit data to equation (1) results in a reduced chi-squared of 0.99, which indicates a near perfect fit and that it is indeed consistent with a wave-like behavior. The added single-slit data fitted to equation (2) results in a reduced chi-squared of 0.21, which is quite small suggesting that the error assigned to the data is too large. This is to be expected though, considering the Poisson method assigns error which is quite large.

Using these fits and calculations of slit-width and separation which can be seen in **Fig. 7**, an average slit-width of 0.075±0.005mm was determined, giving a percent difference of 11.76% from the measurement of 0.085mm provided by the slit manufacturer[2]. The double-slit measurements provided an average slit-separation of 0.041±0.005mm, giving a percent difference of 10.28% from the measurement of 0.0457 provided by the manufacturer[2]; both values further indicating an acceptable fit.

The experiment could have been improved in several ways. For example, it was difficult to get the photons aligned exactly towards the center of the detector slit, therefore the data obtained at the fringes were skewed and had to be removed from the data-set to provide a better fitting of equations (1) and (2). This is because the width of the detector slit blocker does not fully cover the hole to the detector past a micrometer position of around 7mm. For the laser, it was evident that data taken between 0 – 1mm and 6.75 – 7 mm was skewed, so that data was removed from the fit in **Fig 4**. This data being skewed may have in part been responsible for the higher reduced chi-square of the double-slit data for the laser. The data for the lightbulb was found to be skewed between 6.25 – 7mm, and that range of data was removed from the fit in **Fig. 6**.

In conclusion, light exhibits the wave-like behavior of creating interference patterns in instances of using a laser and when it is limited to one photon at a time, even when the singular photons exhibit the particle-like behavior of the photoelectric effect. This result is fascinating because the individual photons had to have behaved like particles in order for the photoelectric effect to have taken place within the PMT, implying that they behaved with wave-particle duality: i.e., exhibited characteristics of both waves and particles simultaneously. Furthermore, since the individual photons exhibited the wave-like behavior of creating an interference pattern consistent with Fraunhofer theory, it implies that the individual photons passed through both of the double-slits simultaneously, thereby interfering with themselves. This phenomenon cannot be explained by classical or Newtonian physics, thereby highlighting the necessity of quantum mechanics.

Citations

1. Gan, K. K., & Law, A. T. (2009). Measuring slit width and separation in a diffraction experiment. European Journal of Physics, 30(6), 1271–1276. https://doi.org/10.1088/0143-0807/30/6/006

2. TWO-SLIT INTERFERENCE, ONE PHOTON AT A TIME: TWS1-B Instructor's Manual, TeachSpin Inc., 2007.

Appendix A: Reported and Measured Slit Dimensions

i. Reported Dimensions Slits[2]

	Source Slit	**Double-slit**	**Detector Slit**
Height	1cm	1cm	1cm
Slit-Width	0.085mm	0.085mm	0.085mm
Slit-Separation	-	0.0457mm	-

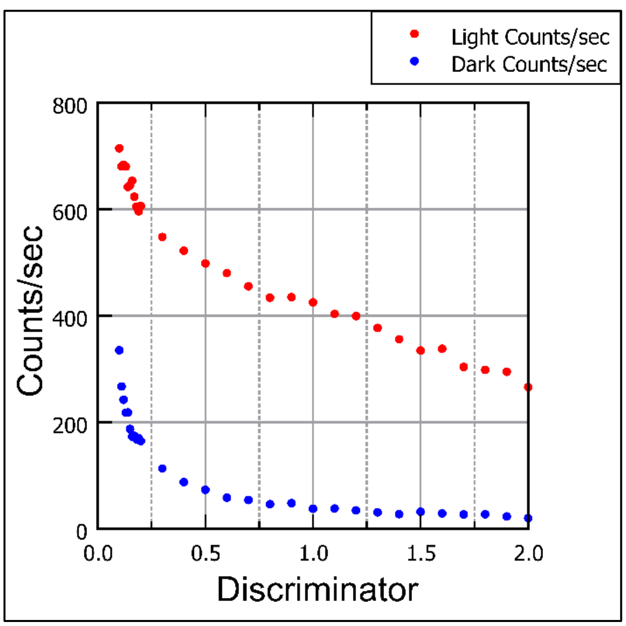
ii. Measured Dimensions of Apparatus:

Box Length: 950.0±0.5mm.

Distance from Laser to Source Slit: 125±0.5mm.

Distance from Double-slit to Detector: approximately 452±0.5mm.

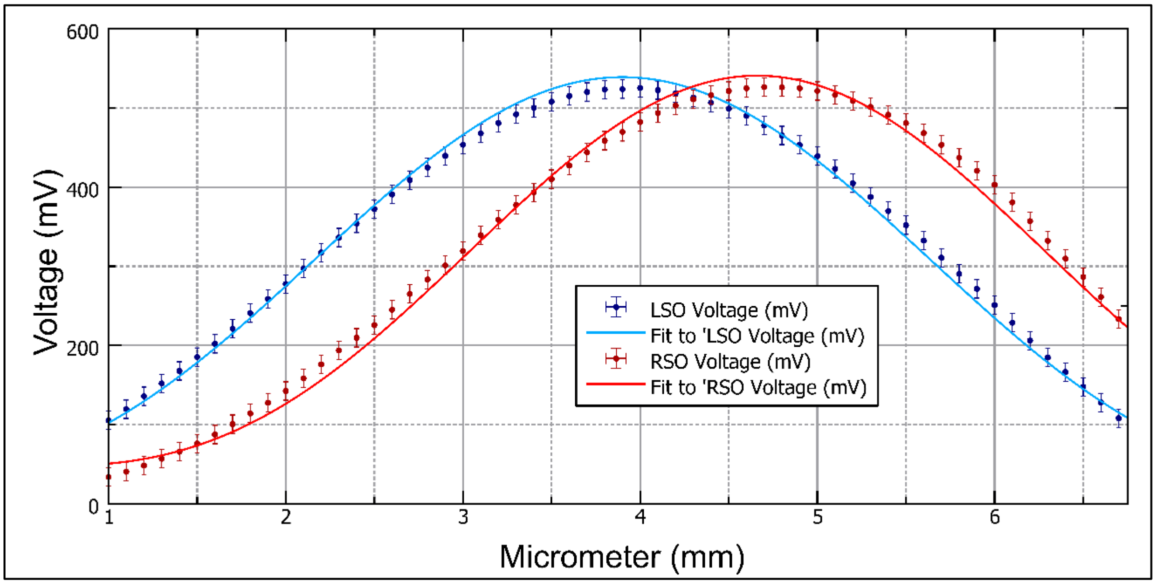
Appendix B: Finding Ideal Fixed Voltage Bias



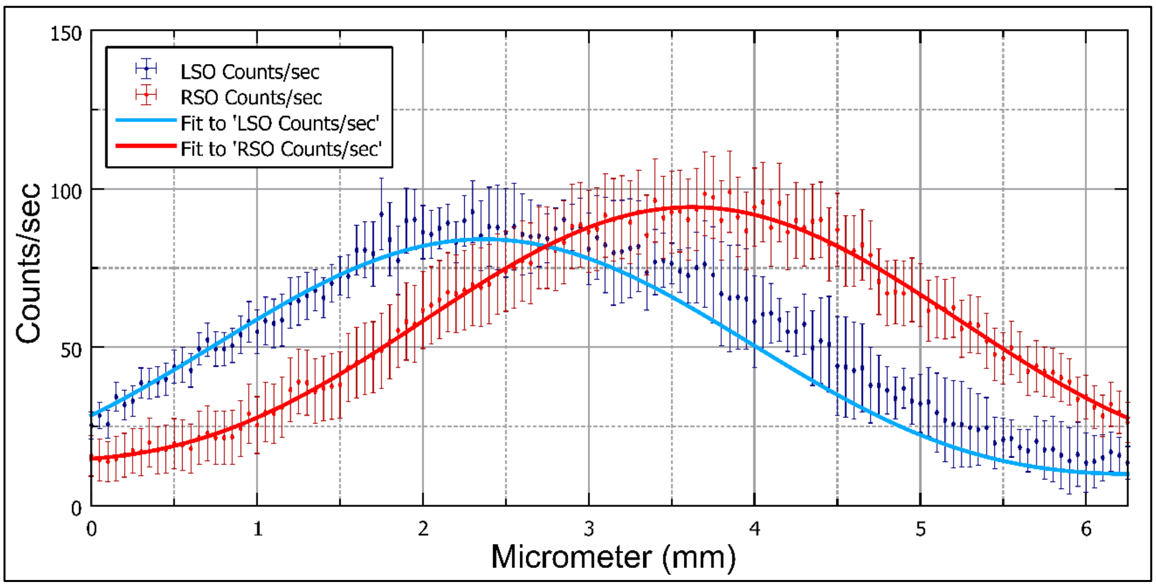
Light and dark counts as a function of discriminator values with voltage bias of 650mV

Using the ideal fixed voltage bias of 650mV found in **Fig. 5**, a plot of light and dark counts as a function of discriminator values was made. 0.2 was found to be an ideal discriminator value as there is a large discrepancy between light and noisy dark counts, and it retained high count values.

Appendix C: Functions of Micrometer Position



Output voltage as a function of micrometer position for left and right slit with a laser fitted to equation (2).



Photon counts per second as a function of micrometer position for left and right slit fitted to equation (2).