Analyzing the Effect of Polarization on the Double Slit Experiment

How will linear polarization impact the intensity and width of the interference pattern in the double-slit experiment?

Physics HL Internal Assessment

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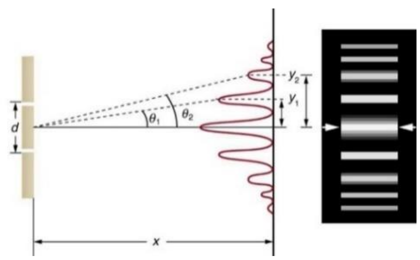
Word Count:

<u>Research Question:</u> How will linear polarization impact the intensity and width of the interference pattern in the double-slit experiment?

<u>Introduction:</u>

The discovery of the particle-wave duality fundamentally changed physics. Leading the way was quantum theory which stated that everything exhibits a wave-like behavior including matter as proved by Louis de Brogile; these waves can be governed by the Schrodinger Equation. Classical physics, such as Newtonian physics, still worked on a macroscopic scale, however, because the wavelengths of matter were extremely small making it have almost no effect in quantum theory. This duality lies at the center of technological innovation today leading the advancements in electron microscopes which exploit the wave-like behavior of electrons to resolve structures smaller than the wavelength of visible light; quantum computers which rely on wave functions to manipulate qubits in superposition; and semiconductors which utilize the quantum tunneling effect.

One of the most fundamental experiments exhibiting this duality is Young's Double Silt experiment. This experiment demonstrated the wave-like property of light. By sending waves of light through two minuscule slits, an interference pattern is observed.



<u>Figure 1:</u> Diagram of Young's Double Slit Experiment with the intensity of light being marked by the peaks. The highest intensity is in between the slits. ('Young's')

However, Einstein proved the particle nature of light through the photoelectric effect. By striking a metal with light, the kinetic energy of the ejected electrons is proportional to the frequency off the light demonstrating it's behavior as discrete particles – specifically photons. If instead of behaving like a wave-like state, it behaved in a particle state, a maximum under the two slits would be expected to occur. Thus, this demonstrates the particle wave duality

<u>Figure 2:</u> The expected intensity if light was a particle. The highest intensity is directly under the slits.

Later, this experiment was extended beyond light into other individual particles, such as electrons, which produce the same pattern if the particles are tallied on the screen. According to quantum theory, as the particle passes through the slits it's in a state of superposition – being in two places at once. However, if the path of the particle is observed, results from the single slit experiment arise. In an attempt to visualize this paradox, this experiment will utilize polarizers as a means to filter out which-path and laser diode instead of emitting individual particles at the source.

Background Information:

According to Huygen's Principle, "every point on a wave front is a source of wavelets that spread out in the forward direction at the same speed as itself" (LibreTexts, '1.7').

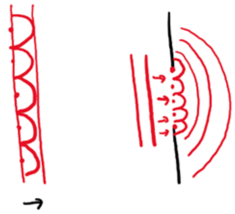


Figure 3: The left demonstrates Huygen's Principle in free space which produced another wave-front. The right demonstrates the principle as it bends around the corner, exhibiting diffraction.

From this principle, constructive and destructive interference occur which generates the interference pattern. Let the distance between the center of the slits be a, the angle between the slit to the direction of the beam be θ, the wavelength be λ, and m be the order. Then the phase of the waves is $a \sin x$. This leads to the following based on the definition of constructive and destructive interference:

$$\text{Constructive Interference: } a sin\theta = m\lambda \ldots (1)$$

$$\text{Destructive Interference: } a sin\theta = \left(m + \frac{1}{2}\right)\lambda \ldots (2)$$

The intensity along this interference pattern can be measured with the following formula:

$$I(\theta) = I_0 \left(\frac{\sin\beta}{\beta}\right)^2 \cos^2\alpha, \text{ where } a = \frac{\pi a \sin\theta}{\lambda} \text{ and } \beta = \frac{\pi b \sin\theta}{\lambda}$$

I_0 is the intensity of the laser, b is the width of the slit, and the other variables are the same as above

The fringes are caused by an absence of intensity which is when $I(\theta) = 0$. Thus the following equation for minima arise:

$$\left(\frac{\sin\beta}{\beta}\right)^2 = 0$$

$$\sin\beta = 0 \ldots(3)$$

$$\cos^2\alpha = 0$$

$$\cos\alpha = 0 \ldots(4)$$

From (3) and (4) the following minima can be defined. Interference is the minima caused by α and diffraction is the minima cause by β. In other words, the diffraction minima create a boundary to where the interference minima appears.

$$\text{Interference minima: } \alpha = \pm\frac{\pi}{2}, \pm\frac{3\pi}{2}, \cdots, \pm\frac{(2m+1)\pi}{2} \text{ or } a\sin\theta = \pm\frac{\lambda}{2}, \pm\frac{3\lambda}{2}, \cdots, \pm\left(m + \frac{1}{2}\right)\lambda \ldots (5)$$

$$\text{Diffraction minima: } \beta = \pm\pi, \pm 2\pi, \cdots, \pm m\pi \text{ or } b\sin\theta = \pm\lambda, \pm 2\lambda, \cdots, \pm m\lambda \ldots (6)$$

Similarly the maxima due to interference can be found with equation (1). However, the maxima may not appear due to the direction also corresponding to a diffraction minima. This order m is said to be missing if there exists a m' that satisfies the following:

$$a \sin\theta = m\lambda \text{ and } b \sin\theta = m'\lambda$$

On a particle level, the double-slit experiment is governed by quantum mechanics. Treating an individual photon, the following wave function can be derived. The $\frac{1}{\sqrt{2}}$ factor appears due to the normalization of equal probabilities of the photon passing through each slit.

$$|\varphi\rangle = \frac{1}{\sqrt{2}}(|x_1\rangle + |x_2\rangle)$$

x_1 and x_2 are the positions of the first and second slit: $x_1 = 0$ and $x_2 = 1$

Through a Fourier Transform the wave equation can be expressed in terms of momentum. In the following equations $\hbar$ (reduced Planck's constant) is expressed in natural units ($\hbar = 1$) to simplify calculations

$$\langle p|\varphi\rangle = \frac{1}{\sqrt{2}}(\langle p|x_1\rangle + \langle p|x_2\rangle) \ldots (7)$$

$$\langle p|x_1\rangle = \frac{1}{\sqrt{2\pi\hbar}}\int_{a_1}^{b_1} \phi(x)e^{-\frac{ipx}{\hbar}}\, dx \ldots (8)$$

$$\langle p|x_2\rangle = \frac{1}{\sqrt{2\pi\hbar}}\int_{a_2}^{b_2} \phi(x)e^{-\frac{ipx}{\hbar}}\, dx \ldots (9)$$

$$\phi(x) = \frac{1}{\sqrt{\delta}} \ldots (10)$$

a_i and b_i denote the left and right boundaries respectively of the ith slit and $\phi(x)$ denotes the state of the wave with respect to position

Let δ denote the slit width. Utilizing the equations (4), (5), (6) to substitute into (3) we can derive and simplify the following.

$$\varphi = \left(\frac{1}{\sqrt{2}}\right)\left(\frac{1}{\sqrt{2\pi}}\right)\left(\frac{1}{\sqrt{\delta}}\right)\left(\int_{x_1-\frac{\delta}{2}}^{x_1+\frac{\delta}{2}} e^{-ipx}\, dx + \int_{x_2-\frac{\delta}{2}}^{x_2+\frac{\delta}{2}} e^{-ipx}\, dx\right)d$$

$$\varphi = \frac{1}{2\sqrt{\pi\delta}}\left(-\frac{i\left(e^{-ip\left(x_1+\frac{\delta}{2}\right)} - e^{-ip\left(x_1-\frac{\delta}{2}\right)}\right)}{p} + -\frac{i\left(e^{-ip\left(x_2+\frac{\delta}{2}\right)} - e^{-ip\left(x_2-\frac{\delta}{2}\right)}\right)}{p}\right)$$

Solving for the real component of this:

$$\mathrm{Re}(\varphi) = \frac{1}{2\sqrt{\pi\delta}}\left(\frac{-\sin\left(-p\left(x_1+\frac{\delta}{2}\right)\right)+\sin\left(-p\left(x_1-\frac{\delta}{2}\right)\right)}{p} + \frac{-\sin\left(-p\left(x_2+\frac{\delta}{2}\right)\right)+\sin\left(-p\left(x_2-\frac{\delta}{2}\right)\right)}{p}\right)$$

$$\mathrm{Re}(\varphi) = \frac{1}{2p\sqrt{\pi\delta}}\left(\sin\left(p\left(x_1+\frac{\delta}{2}\right)\right) - \sin\left(p\left(x_1-\frac{\delta}{2}\right)\right) + \sin\left(p\left(x_2+\frac{\delta}{2}\right)\right) - \sin\left(p\left(x_2-\frac{\delta}{2}\right)\right)\right)$$

Substituting values of x_1 and x_2:

$$\mathrm{Re}(\varphi) = \frac{1}{2p\sqrt{\pi\delta}}\left(\sin\left(p\left(\frac{\delta}{2}\right)\right) - \sin\left(p\left(-\frac{\delta}{2}\right)\right) + \sin\left(p\left(1+\frac{\delta}{2}\right)\right) - \sin\left(p\left(1-\frac{\delta}{2}\right)\right)\right)$$

Letting the $\delta = 0.2$ we can see that the probability distribution is similar to the interference pattern in the double slit experiment

$$\mathrm{Re}(\varphi) = \frac{1}{2p\sqrt{0.2\pi}}(\sin(0.1p) - \sin(-0.1p) + \sin(1.1p) - \sin(0.9p))$$

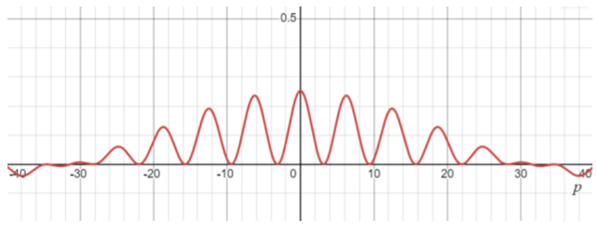


Figure 4: Graph of the probability of the wave function when $\delta = 0.2$, where the x-axis is momentum. In this experiment the probability will be measured in intensity because a laser is used instead of individual particles.

However, if one slit is observed, the wave function collapses, causing the double slit to turn into a single slit. This is because the wave which crosses the double slit is determined, making the probability of one wave 1 while the other is 0, or vice versa. While there exist many ways to observe the 'which-way' of the wave, this experiment will utilize polarizers.

Polarizers are objects which induce polarization which is "an attribute that a wave's oscillations have a definite direction of propagation of the wave" (LibreTexts, '27.8'). While various polarizers exist, this experiment will utilize linear polarizers – specifically absorptive polarizers. Inside these polarizers are certain crystals which produce dichroism, which is the preferential absorption of light in a particular direction.

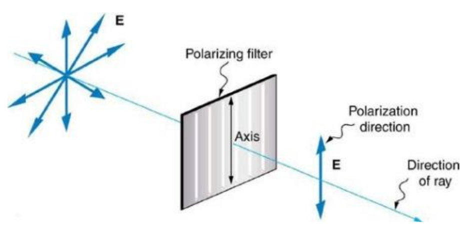


Figure 5: Depiction on how unpolarized light, E, is polarized as it shines through a filter (LibreTexts)

As parts of the unpolarized light are absorbed into the filter, the intensity is decreased, is states in Malus's Law:

$$I = I_0 \cos^2\theta$$

Hypothesis:

Given the information presented in the background I believe that polarization will cause a reduction of intensity as stated by Malus's Law. Furthermore, by utilizing orthogonal polarizations on the double slit to observe the path, I believe the double-slit interference pattern will become a single-slit pattern. This is because the orthogonal polarizations will differentiate between the sources of light going through each slit.

Variables:

Independent Variable:

Table 1: Independent Variable

Independent Variable	How it was Changed	Significance
Polarization	The initial laser was polarized with a rotating linear polarizer that allowed the laser to be polarized at different angles. Furthermore polarizing films were attached to the double slit at orthogonal angles.	The polarization of the laser should decrease intensity, which will be measured by a photoresistor. Furthermore, the usage of the orthogonal polarizing films should collapse the double slit into a single slit experiment

Dependent Variable:

Table 2: Dependent Variable

Dependent Variable	How it was Changed	Significance
Intensity of central node in the interference pattern	Changed as a result of the different initial polarizations of the laser	This change in intensity would lead to the conclusion that intensity would decrease due to polarization of the laser
Existence of a single slit pattern or double slit pattern	Changed as a result of the orthogonal films applied to the double slit	This would show that the double-slit experiment would collapse to a single slit experiment if placed under observation

Controlled Variable

Table 3: Controlled Variables

Control Variable	Effect if Not Controlled	How it was Controlled
Temperature	Increasing temperature may cause thermal fluctuations which would blur the interference pattern compared to lower temperatures as a result of thermal fluctuations	The experiment was conducted inside a garage where the room temperature was set to be constant.
Room Illuminance	Different room illuminance will cause different readings from the photoresistor, impacting the conclusions of the experiment	All the lights were turned off during the runs and the brightness of the laser was set to be constant
Equipment	The same equipment was used, preventing any incorrect readings.	The same laser, polarizers, and photoresistor were used across all experiments

Apparatus:

Table 4: Material List

Item Name	Quantity	Uncertainty	Part Number
Viewing Screen	1	-	PASCO OS-8460
1.2m Optics Bench	1	±0.5mm	PASCO OS-8508
Photoresistor	1	*	EBOOT-5539
Arduino Uno	1	-	A000066
$10k\Omega$ resistor	1	$\pm 500\Omega$	EFR-W0D50-A:MF
650nm Red Diode Laser	1	-	PASCO OS-8525A
Multiple Slit Disk	1	-	PASCO OS-8523
Polarizers	1	±0.5 degrees	PASCO OS-8500
Adjustable Lens Holder	1	-	PASCO OS-8474

(*) The photoresistor has different tolerance values depending on the light levels affecting precise uncertainty or tolerance measurement.

Diagram:

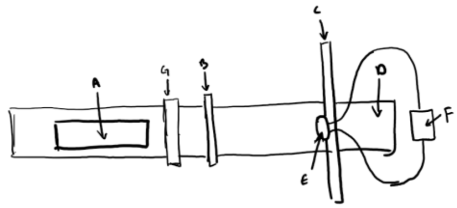


Figure 2: Diagram of the Setup with the following labels:

A. Laser
B. Double Slit with Polarizers attached
C. Viewing screen with photoresistors
D. Optics Bench
E. Photoresistor connected to the Arduino with jumper wires
F. Arduino connected to an external power source
G. Linear Polarizer & Adjustable Lens Holder

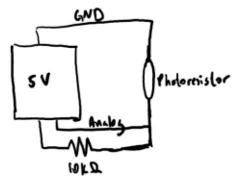


Figure 3: Schematic of the circuit with the photoresistor connected to the 5V and A0 pin of the Arduino

Risk Assessment:

Table 5: Risk Assessment

Equipment	Hazard	Pictogram	Preventive Measures
650nm Red Diode Laser	Eye injury if exposure to direct or reflected beam		The scientist wore laser safety goggles to protect their eyes through the experiment.

Environmental Considerations: There were no environmental considerations detected during this investigation as no waste was produced.

Ethical Considerations: This experiment did not utilize any human or animal subjects, thus no ethical considerations are posed.

Procedure:

Exploring Methods of Procedure:

Initially, I planned to utilize a microscope to place the polarizers on the double slits due to the miniscule width between them. However, the zoom on this was too much, and instead I used a phone camera at 5x zoom and used a double slit with a larger width between them to account for error. Additionally, the single slit experiment was tested (Appendix 1) to draw comparisons between the orthogonal films placed on the double slit. Initial testing of the photoresistor revealed inaccurate results as the voltage varied. Thus, a pull-up resistor as added to ensure a regular supply of voltage, leading to accurate readings.

Procedure:

1. Prepare the double slit with polarization and the photoresistor circuit.

    a. Double slit: Cut an appropriate amount of polarizing film and use the adhesive side to stick it onto one slit. For the other slit, use the orthogonal directed polarization. For clarity, this is done under a camera with 5x zoom.
    b. Photoresistor circuit: Connect the photoresistor to 5V and GND pin. Connect a resistor to the 5V wire. Connect the A0 pin to the 5V wire. Upload the code in Appendix 2
2. Place the photoresistor 20 cm away from the double slit without polarization
3. Add the polarizer before the double the slit and polarize the initial light at 0, 30, 60 and 90, and take readings of the photoresistor
4. Remove the polarizer and attach the film to the double-slits, and observe the interference pattern
5. Repeat Step 3
6. Repeat steps 2-5 for 40, 60, 80, 100 cm
7. Repeat steps 2-6 for Trial 2 and Trial 3

Setup:

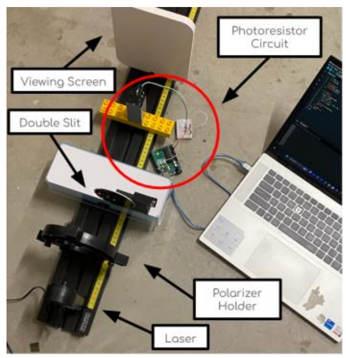


Figure 4: Setup of the Experiment

Data Collection:

Qualitative Data:

1. The more horizontally the polarizer rotated, the less intense the laser became
2. On the viewing screen, the intensity decreased as you moved away from the center
3. Depending on how long the laser had shone on the photoresistor the more sensitive it would become
    a. If a more intense light was shone at the photoresistor, and the intensity deceased, the photoresistor was less prone to change; whereas the photoresistor was more prone to fluctuate if the intensity was suddenly changed from light to dark.
4. As the distance between the viewing screen and double slit increases, the width of each fringe and the boundaries increase
5. When the orthogonal polarizers were used to cover each slit on the double slit, the interference patten created (Appendix 3) closely resembled that of the single slit due to the monotonic pattern without any fringes between the boundaries.

Raw Quantitative Data:

Table 6: 20 cm

Trial	Linear Polarization (Degree) ±0.5 degrees	Polarized Double Slit	Intensity at Central Peak (Analog Reading)	Distance between center and first missing order (cm) ±0.05cm
1	None	Yes	450	0.1

		No	544	0.1
	0	Yes	310	0.1
		No	484	0.1
	30	Yes	216	0.1
		No	404	0.1
	60	Yes	79	0.1
		No	232	0.1
	90	Yes	1	0.1
		No	5	0.1
2	None	Yes	410	0.1
		No	606	0.1
	0	Yes	300	0.1
		No	400	0.1
	30	Yes	210	0.1
		No	350	0.1
	60	Yes	74	0.1
		No	188	0.1
	90	Yes	1	0.1
		No	4	0.1
3	None	Yes	405	0.1
		No	537	0.1
	0	Yes	306	0.1
		No	429	0.1
	30	Yes	224	0.1
		No	338	0.1
	60	Yes	83	0.1
		No	190	0.1
	90	Yes	1	0.1
		No	4	0.1

Table 7: 40 cm

Trial	Linear Polarization (Degree) ±0.5 degrees	Polarized Double Slit	Intensity at Central Peak (Analog Reading)	Distance between center and first missing order (cm) ±0.05cm
1	None	Yes	343	0.3
		No	525	0.2
	0	Yes	260	0.3
		No	352	0.2
	30	Yes	180	0.3
		No	289	0.2
	60	Yes	60	0.3
		No	160	0.2
	90	Yes	0	0.3
		No	4	0.2
2	None	Yes	377	0.3
		No	480	0.2
	0	Yes	255	0.3
		No	386	0.2
	30	Yes	205	0.3
		No	292	0.2
	60	Yes	60	0.3
		No	138	0.2
	90	Yes	0	0.3
		No	5	0.2
3	None	Yes	375	0.3
		No	477	0.2
	0	Yes	230	0.3
		No	363	0.2
	30	Yes	160	0.3
		No	286	0.2
	60	Yes	45	0.3
		No	146	0.2
	90	Yes	0	0.3
		No	2	0.2

Table 8: 60 cm

Trial	Linear Polarization	Polarized Double Slit	Intensity at Central Peak (Analog	Distance between center and first

	(Degree) ±0.5 degrees		Reading)	missing order (cm) ±0.05cm
1	None	Yes	275	0.4
		No	400	0.4
	0	Yes	200	0.4
		No	301	0.4
	30	Yes	124	0.4
		No	263	0.4
	60	Yes	33	0.4
		No	132	0.4
	90	Yes	0	0.4
		No	1	0.4
2	None	Yes	280	0.4
		No	390	0.4
	0	Yes	170	0.4
		No	290	0.4
	30	Yes	124	0.4
		No	232	0.4
	60	Yes	25	0.4
		No	97	0.4
	90	Yes	0	0.4
		No	1	0.4
3	None	Yes	266	0.4
		No	357	0.4
	0	Yes	167	0.4
		No	252	0.4
	30	Yes	120	0.4
		No	196	0.4
	60	Yes	26	0.4
		No	90	0.4
	90	Yes	0	0.4
		No	0	0.4

Table 9: 80 cm

Trial	Linear Polarization (Degree) ±0.5 degrees	Polarized Double Slit	Intensity at Central Peak (Analog Reading)	Distance between center and first missing order (cm) ±0.05cm
1	None	Yes	196	0.6
		No	356	0.7
	0	Yes	113	0.6
		No	246	0.7
	30	Yes	82	0.6
		No	202	0.7
	60	Yes	14	0.6
		No	90	0.7
	90	Yes	0	0.6
		No	0	0.7
2	None	Yes	151	0.6
		No	370	0.7
	0	Yes	138	0.6
		No	288	0.7
	30	Yes	106	0.6
		No	224	0.7
	60	Yes	30	0.6
		No	92	0.7
	90	Yes	0	0.6
		No	1	0.7
3	None	Yes	216	0.6
		No	371	0.7
	0	Yes	144	0.6
		No	254	0.7
	30	Yes	97	0.6
		No	200	0.7
	60	Yes	25	0.6
		No	82	0.7
	90	Yes	0	0.6
		No	0	0.7

Table 10: 100 cm

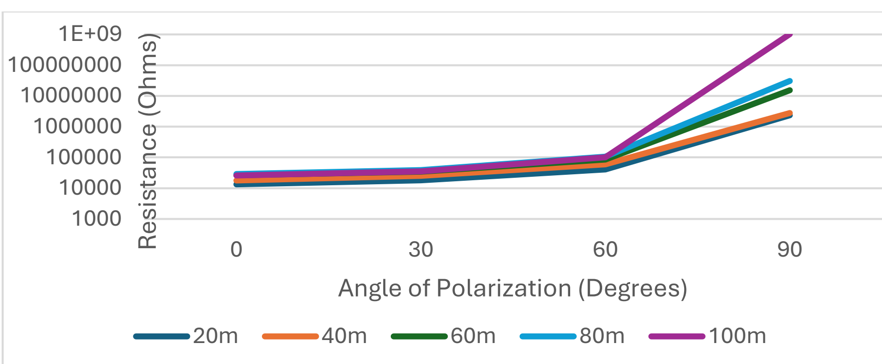
Trial	Linear Polarization (Degree) ±0.5 degrees	Polarized Double Slit	Intensity at Central Peak (Analog Reading)	Distance between center and first missing order (cm) ±0.05cm
1	None	Yes	162	0.9
		No	386	0.9
	0	Yes	107	0.9
		No	278	0.9
	30	Yes	75	0.9
		No	218	0.9
	60	Yes	17	0.9
		No	116	0.9
	90	Yes	0	0.9
		No	0	0.9
2	None	Yes	185	0.9
		No	420	0.9
	0	Yes	110	0.9
		No	290	0.9
	30	Yes	84	0.9
		No	237	0.9
	60	Yes	18	0.9
		No	96	0.9
	90	Yes	0	0.9
		No	0	0.9
3	None	Yes	190	0.9
		No	412	0.9
	0	Yes	114	0.9
		No	286	0.9
	30	Yes	85	0.9
		No	221	0.9
	60	Yes	16	0.9
		No	66	0.9
	90	Yes	0	0.9
		No	0	0.9

Data Processing/Analysis:

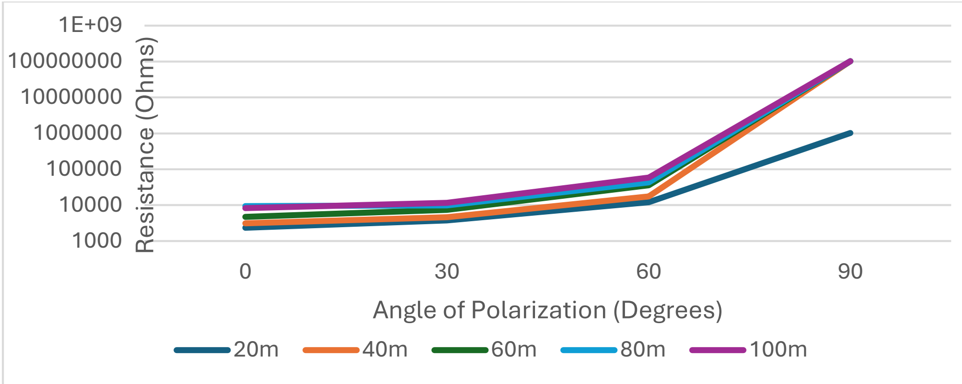
To convert from analog to resistance, the following formulas are used to derive the tables in Appendix 3, where x is the analog value of the Arduino:

$$\text{Voltage} = \frac{5}{1023} \cdot x \quad \text{Resistance} = 10000 \cdot \frac{\left(5 - \frac{5x}{1023}\right)}{\frac{5x}{1023}}$$

Graph 1: Graph of the Average Resistance against Polarization Degree for Non-Polarized Double Slit



Graph 2: Graph of the Average Resistance against Polarization Degree for Polarized Double Slit



Uncertainty Calculations:

Because the uncertainty is 0.5 degrees for the polarization, 0.5mm for the measuring the placement of the polarizer holder, double slit, and photoresistor circuit, and 500Ω for the resistor, the following uncertainty exists for every measured experiment:

$$\frac{0.5}{360}+\frac{0.5\cdot10^{-3}}{1.2}+\frac{0.5\cdot10^{-3}}{1.2}+\frac{0.5\cdot10^{-3}}{1.2}+\frac{500}{10000}=5.3\%$$

An average tolerance value of a resistor of 5% is used to calculate the uncertainty of the photoresistor. Therefore, the total uncertainty is 10.3% for measuring the intensity. However, an additional uncertainty has to be added to account for distance measurement between central node and missing order. These uncertainties will be averaged across trials and measurements:

$$\frac{\frac{0.05}{0.1}+\frac{0.05}{0.1}+\frac{0.05}{0.3}+\frac{0.05}{0.2}+\frac{0.05}{0.4}+\frac{0.05}{0.4}+\frac{0.05}{0.6}+\frac{0.05}{0.7}+\frac{0.05}{0.9}+\frac{0.05}{0.9}}{10}*100=19.3\%$$

Therefore, the uncertainty when measuring the distance between the central node and missing order is 39.6%.

Calculation of Missing Order:

From the double slit we know that the slit distance is 0.5mm, and each slit width is 0.08mm. Thus, the distance from the center of the first to second is $0.5+\frac{0.08}{2}*2=0.58$. Furthermore, the laser has a wavelength of 650 nm. Therefore, using the equations (1) and (6), the following equations can be found:

$$0.58 sin\theta = m650(10^{-3})$$

$$0.08 sin\theta = m'650(10^{-3})$$

Solving this system we get: $m=7.25m'$. As both m and m' have to be the minimum integers that satisfy the equations, m' is set to 1 and m is set to 7. Therefore $\theta = arcsin(\frac{650(10^{-3})}{0.58}) = 0.0078$ radians

Using the experimental values we can find percent error, with the following formulas:

$$\text{Angle} = \arctan\left(\frac{d_1}{d_2}\right)$$

$$\text{Percent Error} = \frac{(theoretical-measured)}{theoretical}*100$$

d_1 is the distance from central peak to the missing order and d_2 is the distance from slit to photoresistor

Table 11: Percent Error of Measured Angle for Polarized Double Slit

Distance from Photoresistor to Slit (cm) ±0.5mm	Distance from central peak to missing order (cm) ±0.5cm	Angle (radians)	Percent Error
20	0.1	0.0050	35%
40	0.3	0.0075	3.8%
60	0.4	0.0067	14%
80	0.6	0.0075	3.8%
100	0.9	0.009	15%

Table 12: Percent Error of Measured Angle for Non-Polarized Double Slit

Distance from Photoresistor to Slit (cm) ±0.5mm	Distance from central peak to missing order (cm) ±0.5cm	Angle (radians)	Percent Error
20	0.1	0.0050	35%
40	0.2	0.0050	35%
60	0.4	0.0067	14%
80	0.7	0.0087	12%
100	0.9	0.009	15%

Discussion of the Data:

Individual graphs are shown in Appendix 4. Error bars were used to show the uncertainty of the degree measured. The best fit exponential line of the resistance against polarization demonstrates high r^2 values demonstrating their correlation. This is expected because the resistance against polarization graph should follow the trace of $\frac{1}{\cos^2 x}$ as derived below, which resembles an exponential graph for degrees between 0 and 90.

$$\text{From Malus's Law: } I = I_0 \, cos^2 \, x$$

$$10000 * \frac{5 - \frac{5 I_0 \, cos^2 \, x}{1023}}{\frac{I_0 \, cos^2 \, x}{1023}} = \frac{1023}{I_0 \, cos^2 \, x} * 5 * 10000 - 10000$$

Factoring out the constants, it is evident that the resistance against polarization graph resembles the graph of $\frac{1}{\cos^2 x}$.

Furthermore, as demonstrated in Table 11 and 12, there is no significant difference between the location of missing order between polarized and non-polarized slits. The fluctuations of the percentage errors can be attributed to the measuring equipment used to find the distances and the lack of preciseness it had, as demonstrated in the high uncertainty found when measuring.

Additionally, the collapsing of the double-slit experiment can be attributed to the fact that polarization removes the probabilistic nature of 'which-way' the wave will take, as it is being observed.

Evaluation:

Conclusion:

The aim of this experiment was to explore how the interference pattern would be impacted by the polarization of the double slit experiment. While analyzing the data it seems that the intensity decreases if a polarization is induced, whereas the distance of the missing order doesn't change. The change in intensity is expected as during the polarization a single-slit pattern is found. As a result, the waves don't interfere constructively, reducing the total intensity. However, all the resistance graphs follow the same trend of an exponential function, which graphed on Excel shows a strong Pearson Correlation Coefficient of 0.9895, demonstrating the validity of Malus's Law. However, this graph may not correctly predict the resistance for angles close to 90 degrees as it overshoots in regard to the resistance values as the values reach giga-ohms. This is impossible for the given photoresistor to produce as it's not constructed with the materials to do so. Therefore, in conclusion, by inducing polarization, the double-slit interference pattern becomes a single-slit pattern which reduces the intensity of the central peak without affecting the missing order distance.

Strengths and Weaknesses:

a. Strengths:
    1. The analog output from the photoresistor and Arduino provided an analytical way to assess how the intensity changed as a result of a change in the angle of polarization.
    2. The varying distances of 20, 40, 60, 80, 100 cm and three trials allowed for more data to be collected, ensuring a fair and equal test.
    3. The measuring bench provided a level platform for the laser double slit and photoresistor.
b. Limitations and Weaknesses:
    1. Scratches or dust collected on the polarizer or the polarizing film may have diffracted the light, causing a reduced intensity.
    2. The measurement of the distance from the central node to the missing order, especially for small distances such as 20cm and 40cm away have high uncertainty because of the lack of precision of a ruler.

Table 13: Weaknesses and Improvements

Weakness	Impact of Weakness	Suggested Improvement
Intensity on Photoresistor (Systemic Error, Methodological)	The sudden change in intensity may have caused erroneous measurements in analog value. Because the photoresistor was placed in front of a continuous stream of light, the resistor may have grown accustomed to the specific intensity, causing a decreased sensitivity to change in intensity. As a result, this would effect both voltage and resistance readings.	By turning off the laser after every measurement, the photoresistor can become accustomed to the darkened room again. Therefore, by setting constant 'cool-down' times of the laser, the photoresistor can return to its nominal value.
Placement of the Photoresistor (Systemic Error, Methodological)	As the photoresistor was moved, the photoresistor may have been altered, leading to different readings, affecting the end value.	By constructing a custom photoresistor holder through 3d-printing or securing the photoresistor more tightly, there will be a reduction in movement of the photoresistor, leading to more accurate readings.
Placement of Polarizing Films (Human Error)	Due to the small sizes of the slit widths and separation, the placement of the polarization may not have fully covered each slit. Although a single-slit pattern was observed, the precise nature may not have been observed by the human eye.	Instead of aligning the polarizers on the double slit, they can be pre-connected outside to properly align the edges to ensure each slit is covered with a different film.

Extensions:

A future investigation on this experiment may investigate the behavior of different particles – electrons, protons, and neutrinos – are impacted by observation in the double slit experiment. Additionally, by altering the number of slits and observing different slits, a more accurate representation will be gained on the impact of observing a quantum state. The understanding of this effect may lead to notable contributions in quantum sensors which exhibit extreme precision; quantum materials enabling the creation of the next generation of technologies; and quantum biology to explain phenomena such as photosynthesis efficiency.

Works Cited:

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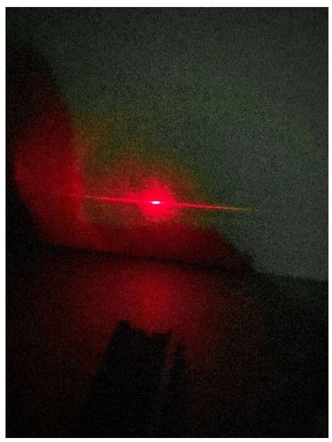
Appendices:

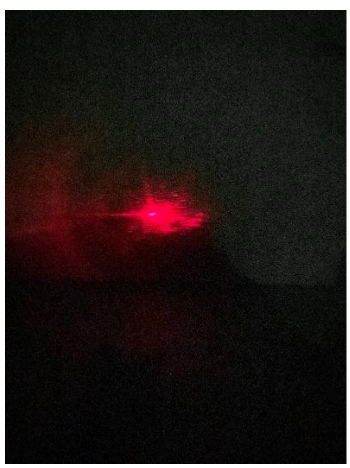
Appendix 1: Photos of the Interference Pattern:

Appendix 1a: Single Slit Experiment:

Appendix 1b: Double Slit Experiment:



Appendix 1c: Double Slit Experiment with Polarizers Attached:



Appendix 2: Code used for the Arduino:

```
int idx = 0;
int val[100];

void setup() {
  pinMode(A0, INPUT);
  Serial.begin(9600);
}

void loop() {
  int x = analogRead(A0);
  if(idx == 100){
    double sum = 0;
    for(int i = 0; i < 100; i++){
      sum += val[i];
    }
    Serial.println(sum/100);
    idx = 0;
  }
  val[idx] = x;
  idx++;
}
```

Appendix 3: Average Data Tables for Voltage and Resistance

Appendix 3a: Table 14: Data Table for Voltage for Non-Polarized Slits (Volts)

	20cm	40cm	60cm	80cm	100cm
Control	2.74845226	2.414467	1.8686869	1.7872271	1.984359726
0 degrees	2.13913327	1.793744	1.3734115	1.2838058	1.391332682
30 degrees	1.77908113	1.412512	1.1257739	1.0198762	1.10133594
60 degrees	0.99380906	0.723363	0.5197133	0.4301075	0.452916259
90 degrees	0.02117954	0.017921	0.0032584	0.0016292	0

Appendix 3b: Data Table for Resistance for Non-Polarized Slits (Ohms)

	20cm	40cm	60cm	80cm	100cm
Control	819.205691	10708.5	16756.757	17976.299	15197.04433

0 degrees	13373.9528	17874.66	26405.694	28946.701	25936.76815
30 degrees	18104.3956	25397.92	34413.893	39025.559	35399.40828
60 degrees	40311.4754	59121.62	86206.897	106250	100395.6835
90 degrees	2350769.23	2780000	15335000	30680000	1022990000

Appendix 3c: Table 15: Data Table for Voltage Polarized Slits (Volts)

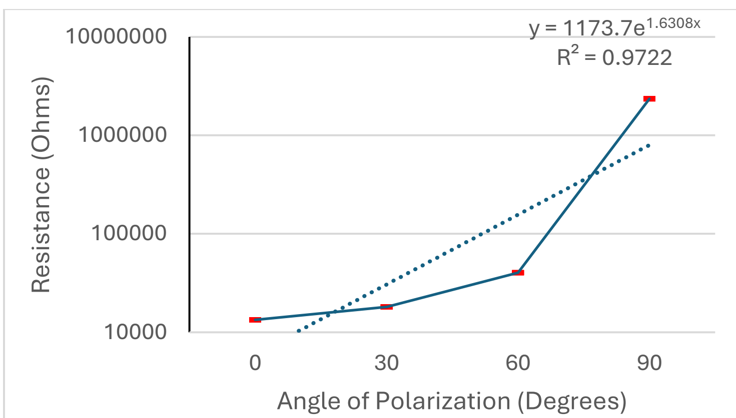
	20cm	40cm	60cm	80cm	100cm
Control	2.060932	1.7839687	1.3375692	0.9172369	0.8748778
0 degrees	1.492343	1.2137504	0.8748778	0.4806126	0.5392636
30 degrees	1.058977	0.8879114	0.5995438	0.4643206	0.3975236
60 degrees	0.38449	0.2688172	0.1368524	0.1124145	0.083089
90 degrees	0.004888	0	0	0	0

Appendix 3d: Data Table for Resistance for Polarized Slits (Ohms)

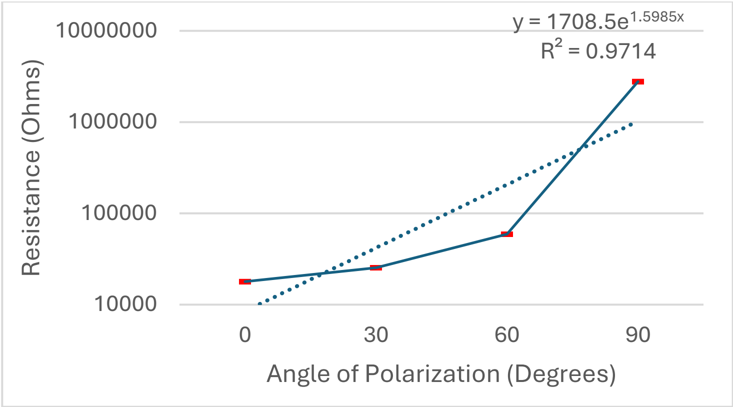
	20cm	40cm	60cm	80cm	100cm
Control	1426.087	1802.7397	2738.1242	4451.1545	4715.0838
0 degrees	2350.437	3119.4631	4715.0838	9403.3898	8271.9033
30 degrees	3721.538	4631.1927	7339.6739	9768.4211	11577.869
60 degrees	12004.24	17600	35535.714	43478.261	59176.471
90 degrees	1022000	102299000	102299000	102299000	102299000

Appendix 4: Graphs of Average Resistance Value for Non-Polarized Double Slit

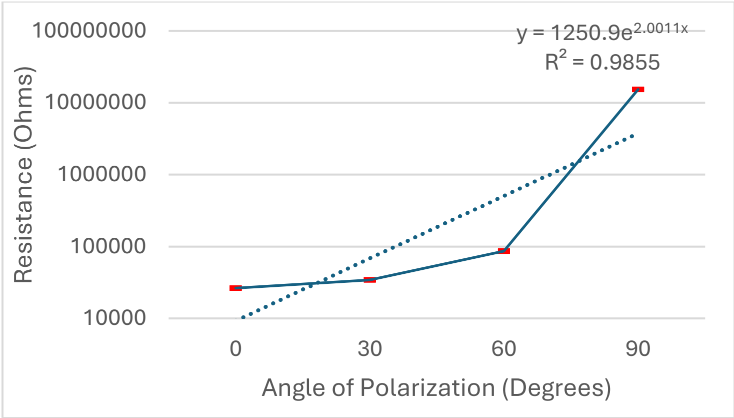
Appendix 4a: 20 cm:



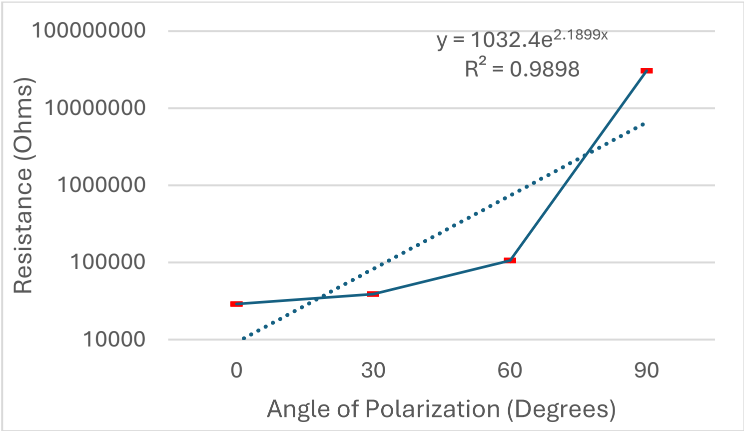
Appendix 4b: 40 cm:



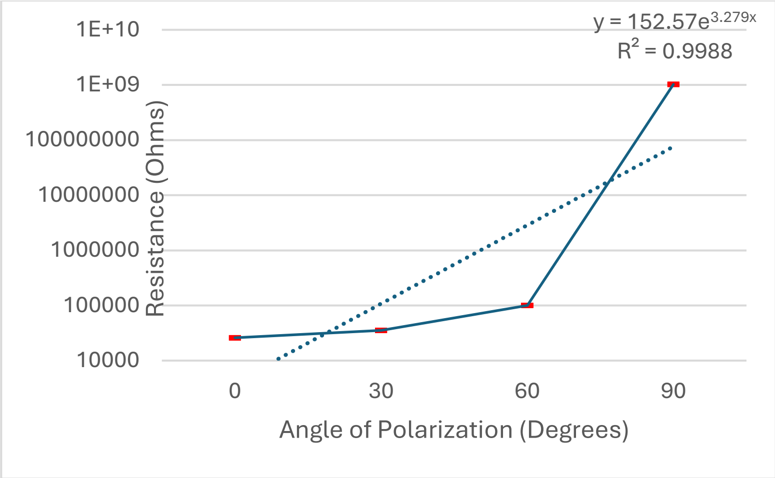
Appendix 4c: 60 cm:



Appendix 4d: 80 cm:

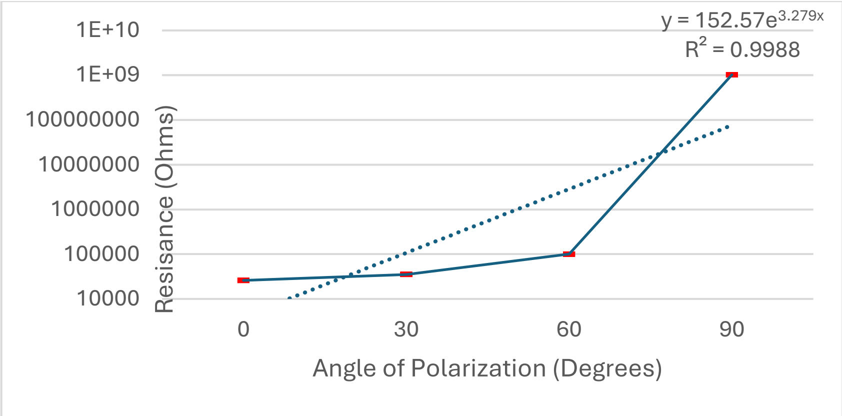


Appendix 4e: 100 cm:

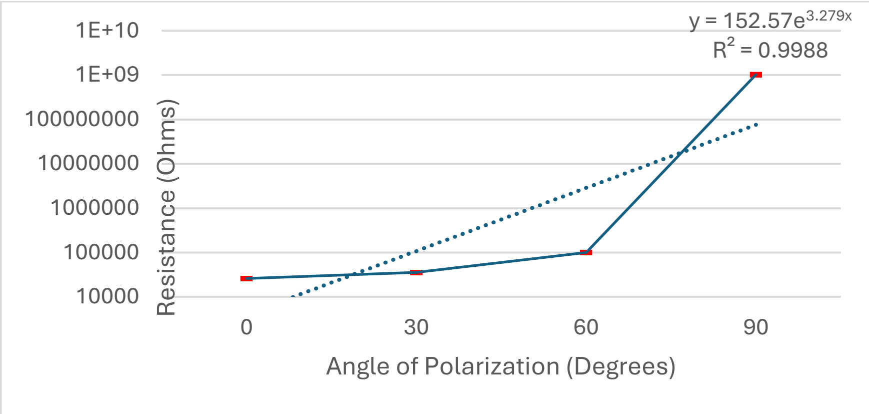


<u>Appendix 5: Graphs Average Resistance Value for Polarized Double Slit</u>

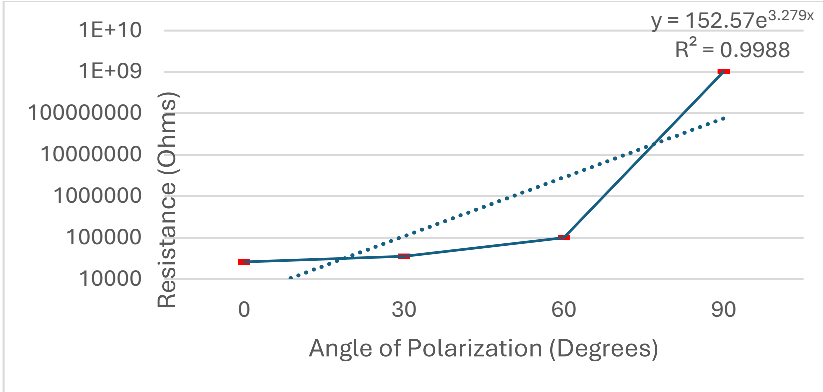
<u>Appendix 5a: 20 cm:</u>



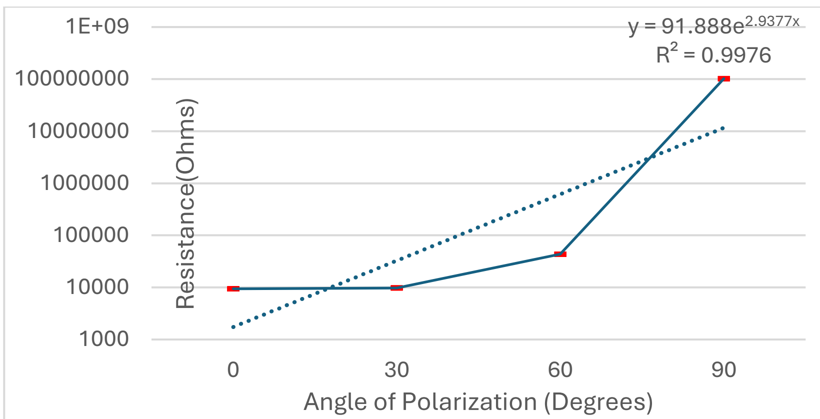
<u>Appendix 5b: 40 cm:</u>



<u>Appendix 5c: 60 cm:</u>



Appendix 5d: 80 cm:



Appendix 5e: 100 cm: