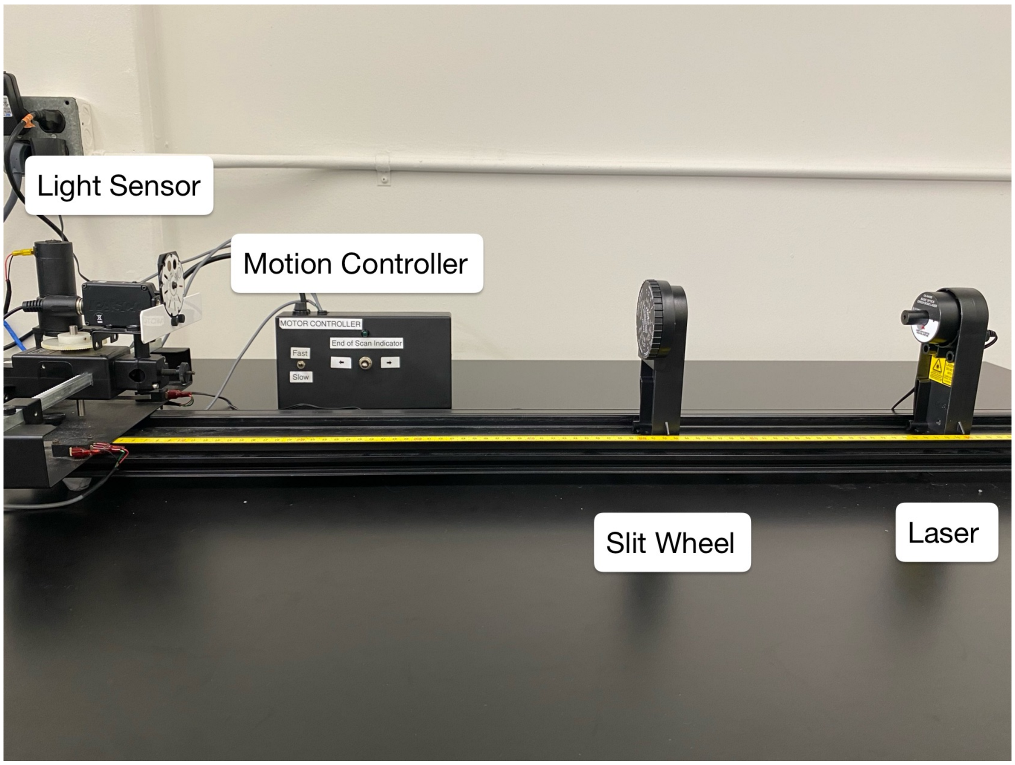
Physics
UNIVERSITY OF TORONTO

Interference and Diffraction of Light



Revisions

2024	C. Lee, T. Vahabi
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This experiment uses a low powered red laser. Never look into the laser beam.

Introduction

Observations of light passing through narrow openings show that light spreads out behind the opening and forms a distinct pattern on a distant screen. By scanning the pattern with a light sensor and plotting light intensity versus distance, differences and similarities between interference and diffraction are examined. Observation of diffraction intensity can be used in a simple quantum mechanical treatment to confirm the Heisenbergs uncertainty principle.

Diffraction

When diffraction of light occurs as it passes through a slit, the angle to the minima (dark spots) in the diffraction pattern is given by

$$a \sin\theta = m'\lambda \quad \text{(m'=1,2,3,...)} \tag{1}$$

where a is the slit width, θ is the angle from the center of the pattern to the m'th minimum, λ is the wavelength of the light, and m' is the order of diffraction (1 for the first minimum, 2 for the second minimum, ...counting from the center out).

In Figure 1, the laser light pattern is shown just below the computer intensity versus position graph. The angle θ is measured from the center of the single slit to the first minimum, so m' = 1 for the situation shown in the diagram.

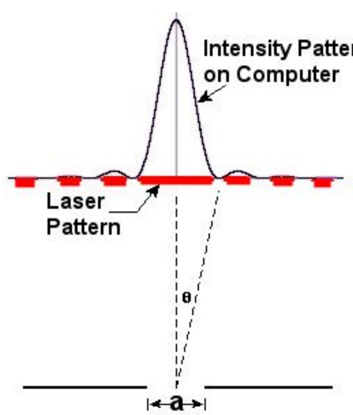

Figure 1: Single-Slit Diffraction

Double-Slit Interference

When interference of light occurs as it passes through two slits, the angle from the central maximum (bright spot) to the side maxima in the interference pattern is given by

$$d \sin\theta = m\lambda \quad \text{(m=1,2,3,...)} \tag{2}$$

where d is the slit separation, θ is the angle from the center of the pattern to the mth maximum, λ is the wavelength of the light, and m is the order (0 for the central maximum, 1 for the first side maximum, 2 for the second side maximum, counting from the center out). In Figure 2, the laser light pattern is shown just below the computer intensity versus position graph.

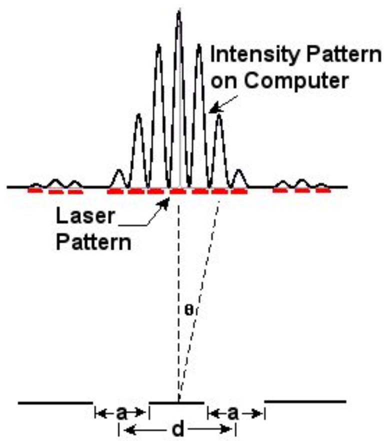

Figure 2: Double-Slit Interference

The angle θ is measured from the midway between the double slit to the second side maximum, so m equals two for the situation shown in the diagram.

Intensity in the diffraction pattern

Light intensity is proportional to the square amplitude of the wave producing it (E^2, where E is the electric field amplitude). By using the concepts from superposition of waves French [1971] we obtain:

$$I(\phi) = I(0) \left(\frac{\sin \phi}{\phi} \right)^2 \quad \text{where} \quad \phi = \frac{\pi\, a}{\lambda} \sin \theta \tag{3}$$

The first intensity minimum is located at $\theta = \sin^{-1}\left(\frac{\lambda}{a}\right)$ according to equation 2

Hardware and Setup

The hardware for the experiment is shown in figures below:

light sensor mounted on a scanner arm and a rotary encoder (figure 4) . The encoder monitor the movement of the scanner along the arm while the light sensor is measuring the light level. The low rpm driving motor drives the light sensor along the linear translator between two switch stops (14 cm travel distance). It can be operated at low speed for data collection or at a higher speed for moving the sensor to a desired position on the linear translator.

laser diode: mounted on the rail with dials to control the angle of the laser. The angle can be adjusted in the horizontal and vertical directions to aim the light at the center of the sensor. These control do not adjust the orientation of any patterns on the sensor.

slit disks: mounted in a lens holder (figure 3). Each slit disks has a set of similar slits (in width or separation) mounted in the same orientation, except for the 'comparison slits' that are rotated by 90°. You can swap out slit disk from the same lens holder as needed, and rotate the disk inside its holder to select the correct slit.

The basic setup shown in figure 4 should be sufficient for most experiments. The laser light and sensor are placed at opposite ends of the rigid optics track. The slit disk is placed close to the laser source and rotated into position. To align the instrument

- Use the scanner motor to move the sensor to the middle of its track
- Switch the laser on and adjust the angle until it hits the sensor slit.
- Place the diffraction grating into a lens holder a few centimeters from the laser, with the disk slide of the holder closest to the laser.
- Adjust the laser beam again if necessary.
- Move the sensor back so that the laser pattern no longer hits the sensor.

When taking measurements, start with the sensor slit on #6 and gain switch on x10. You can adjust this later if the sensor is saturated with too much signal, or noisy with low signal amplitude.

Figure 3: Mounting the Slits

Familiarization with the patterns

- Start with the single slit wheel setup to 0.16 mm. Attach a small piece of paper to the sensor aperture bracket. Look at the pattern.

Figure 4: Scanner with Light Sensor

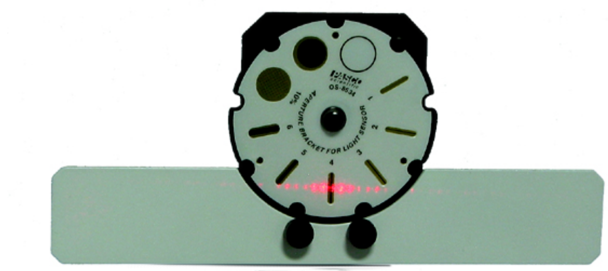

Figure 5: Aligning the Light Sensor

- Select the combination slits from the double slit wheel. Look at the pattern produced by each of the four combinations. Draw a diagram of each slit combination and the corresponding diffraction pattern. Note that the single slit from the combination is always 0.04 mm

Single slit exercise

In this exercise you will measure the light intensity as a function of distance along the diffraction pattern. After measuring a full pattern you can measure the distance between the peaks and troughs of the data and use the measurements to find the width of the slit according to equation 1. The workstation attached to the equipment has the "Interference and Diffraction" to run the data collection. The program also provides 'cursors' to measure the locations of features on the image and to export the data in a text file.

Since you are measuring visible light in this experiment, all sources of visible light hitting the sensor will affect the measurement. You should measure with the room lights off when possible, or block the light in some other way. Even in a dark room the light from the computer monitor, laptops, and cell phones *will* interfere with the measurement.

- Mount the single slit wheel with the 0.04 mm slit.
- Move the light sensor to one side of the laser pattern.
- Click on the **Start** arrow button in the application(upper left corner), turn on the motor, then turn **ON** the acquisition to scan the pattern.
- Turn **OFF** the acquisition when you have finished the scan. The acquisition turns off by itself when the light sensor reaches the end of travel and hits the stop-switch.

- The program allows you to use two pairs of cursors to get the intensity and position along the pattern. Cursors usually reside at the left of the graph. You may save the numerical file in a temporary computer directory and/or print the graph.
- You may have to change the gain setting on the light sensor (1x, 10x, 100x) depending on the intensity of the pattern. You can also try slit #4 on the mask on the front of the light sensor to change the intensity of the light.

Using your light-intensity measurement, determine the slit width using Equation 1, and quantify the errors in your slit width.

Double slit exercise

In this experiment you will use the double slit disk to produce the interference pattern on the sensor. Using similar techniques to the single slit experiment you will need to find the slit separation and the slit width.

- Replace the single slit disk with the multiple slit wheel. Set it on slit separation 0.25 mm (d) and slit width 0.04 mm (a).
- Set the light sensor aperture bracket to slit #4.
- Apply the same steps as before (single slit procedure)
- To measure the small separations Zoom into the central maximum use the "Interference and Diffraction" application, and use cursors to measure the distance as before. For the interference pattern you need to measure maxima-to-maxima distance. For the diffraction pattern you need maxima-to-minima distance.
- Determine the slit separation using Equation 2. You should measure the locations of a few maxima and find the average value of d. Compare your measured slit separated with the stated value on the wheel.
- Determine the slit width using Equation 1 and the distance between the central maximum and the first minimum in the diffraction pattern (not interference pattern). Compare your measured slit width with the stated value on the wheel.
- Repeat the steps above for the interference patterns for two other double slits. Estimate the errors.

Using Python

There are (at least) two ways to use Python to help calculate the slit width and separation in this experiment

Measure the feature locations using the cursors and use these values to calculate average values of width and separation (as above). This requires you to manually determine the locations of peaks and troughs but doesn't require fitting the $\frac{\sin(x)}{x}$ function. You visually check your calculation by plotting the collected data and a simulated pattern on the same plot.

Export the data from the application and fit the appropriate $\frac{\sin(x)}{x}$ function with Python (e.g., using 'curve_fit'). You no longer need to manually measure feature locations in the application but you will need to fit a $\frac{\sin(x)}{x}$ function.

You should use both methods to calculate the slit width and separation, and discuss the sources of error in each method.

Quantum mechanical interpretation

The Heisenberg uncertainty principle McIntyre [2022] states that the simultaneous measurements of the momentum and position (or the energy and time) for a moving particle entails a limitation on the precision (standard deviation) of each measurement. Namely: the more precise the measurement of position, the more imprecise the measurement of momentum, and vice versa. In the most extreme case, absolute precision of one variable would entail absolute imprecision regarding the other. If we consider a pack of photons characterized by position uncertainty $\Delta\, y$ and momentum uncertainty $\Delta\, p$, we can express Heisenberg's relation as:

$$\Delta\, y \cdot \Delta, p \geq \frac{h}{4\pi} \tag{4}$$

Where $h = 6.6262 \times 10^{-34}\mathrm{J} \cdot \mathrm{s}$ is Planck's constant. For a pack of photons passing through a slit of width a we have $\Delta\, y = a$. In order to estimate $\Delta\, p$, we assume that photons reaching the slit move only in the direction perpendicular to the slit (x-direction), but after passing through the slit, they will have velocity components in both directions (x and y). The ν_y component of photon velocity is given by the intensity distribution in the diffraction pattern. Defining by θ_1 the angle of the first minimum of diffraction, we can express the uncertainty of velocity and momentum as:

$$\Delta\, \nu_y = c \sin\theta_1 \quad \text{(c is the speed of light)}, \tag{5}$$

$$\Delta\, p_y = \frac{h}{\lambda} \sin\theta_1, \tag{6}$$

(using the de Broglie relationship: $\frac{h}{\lambda} = p$.) The angle θ_1 of the first diffraction minimum can be determined from the experimental setup geometry (see Figure 1 and Equation 1) and the momentum uncertainty results as:

$$\Delta\, p_y = \frac{h}{a} \tag{7}$$

Combining $\Delta\, y$ with $\Delta\, p_y$ in equation 2, we obtain the uncertainty relation:

$$\Delta\, p_y \cdot \Delta\, t = h \geq \frac{h}{4\pi} \tag{8}$$

Experimentally, we can obtain the angle θ_1 from the position of the first minimum:

$$\tan\theta_1 = \frac{l}{b} \quad \text{(see Figure 1)} \tag{9}$$

By substituting this relation into equation (6), we obtain

$$\Delta\, p_y \frac{h}{\lambda} \sin\left(\tan^{-1}\frac{l}{b}\right). \tag{10}$$

Equation (8) becomes

$$\frac{ah}{\lambda} \sin\left(\tan^{-1}\frac{l}{b}\right) = h \geq \frac{h}{4\pi} \tag{11}$$

so then

$$\frac{a}{\lambda} \sin\left(\tan^{-1}\frac{l}{b}\right) = 1 \tag{12}$$

Experimental verification:

- Measure the half width of the central maximum (l) for three different single slit widths (a). Measure the distance between the light sensor aperture and the laser aperture (b).
- Verify Equation (9). Carefully estimate the errors and discuss about confirming or not Heisenberg's uncertainty principle by using this experimental verification.

Questions

1. What physical quantity is the same for the single slit and the double slit?
2. How does the distance from the central maximum to the first minimum in the single-slit pattern compare to the distance from the central maximum to the first diffraction minimum in the double-slit pattern?
3. What physical quantity determines where the amplitude of the interference peaks goes to zero?
4. In theory, how many interference maxima should be in the central envelope for a double slit with d = 0.25 mm and a = 0.04 mm?
5. How many interference maxima are actually in the central envelope?

The National Instruments interface was setup and programmed by Larry Avramidis. Larry also built the low rpm motor driving the linear translator. For similar experiments, see the PASCO experiment written by Hanks [2022] and the PHYWE [2.3.02] publication.

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