Experiment 5:
Polarization and Interference

Nate Saffold
nas2173@columbia.edu

Office Hour: Mondays, 5:30PM-6:30PM @ Pupin 1216

INTRO TO EXPERIMENTAL PHYS-LAB
1493/1494/2699

Introduction

- Outline:
  - Review of physics:
    1. Electromagnetic waves
    2. Polarization of an EM wave
    3. Interference and diffraction (double and single slit experiments)
  - Polarization and Interference experiment:
    1. Description of the apparati
    2. Data analysis
  - Tips for the experiment

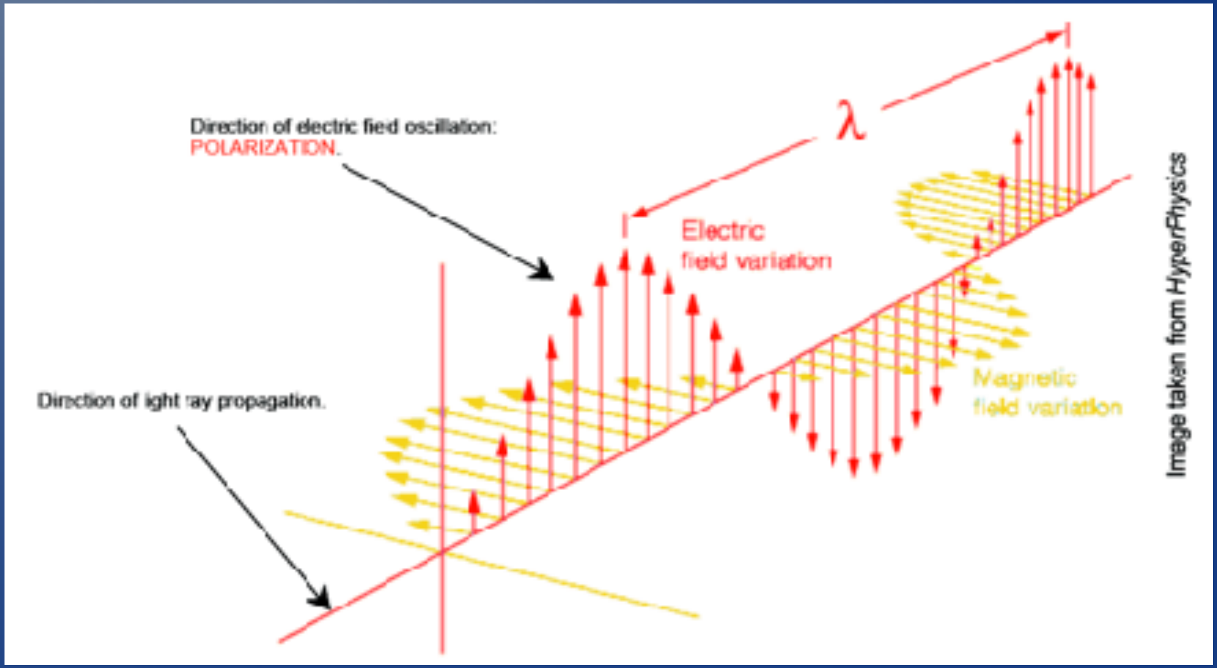
Electromagnetic waves

- **Electromagnetic wave** = oscillating electric and magnetic fields
- An EM wave propagates in vacuum at the speed of light

$$c = 299\,792\,458 \text{ m/s} \simeq 3 \times 10^8 \text{ m/s}$$

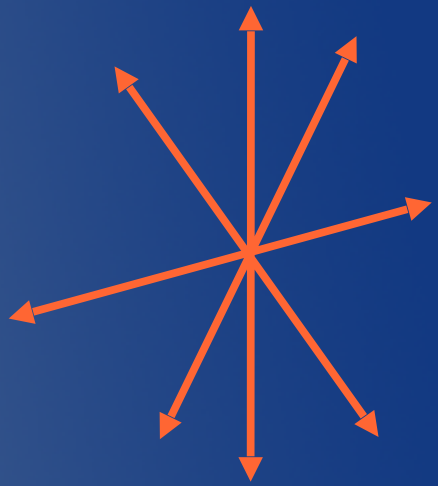
- Electric and magnetic fields are always perpendicular to each other

(James Clerk Maxwell… Pretty smart guy…)



Polarization

- **Polarization of a light wave** = direction of oscillation of the electric field
- Every day light is usually *unpolarized*. All directions of the electric field are *equally probable*.
- ***Linearly* polarized light** = the direction of oscillation at a particular point in space is always the same

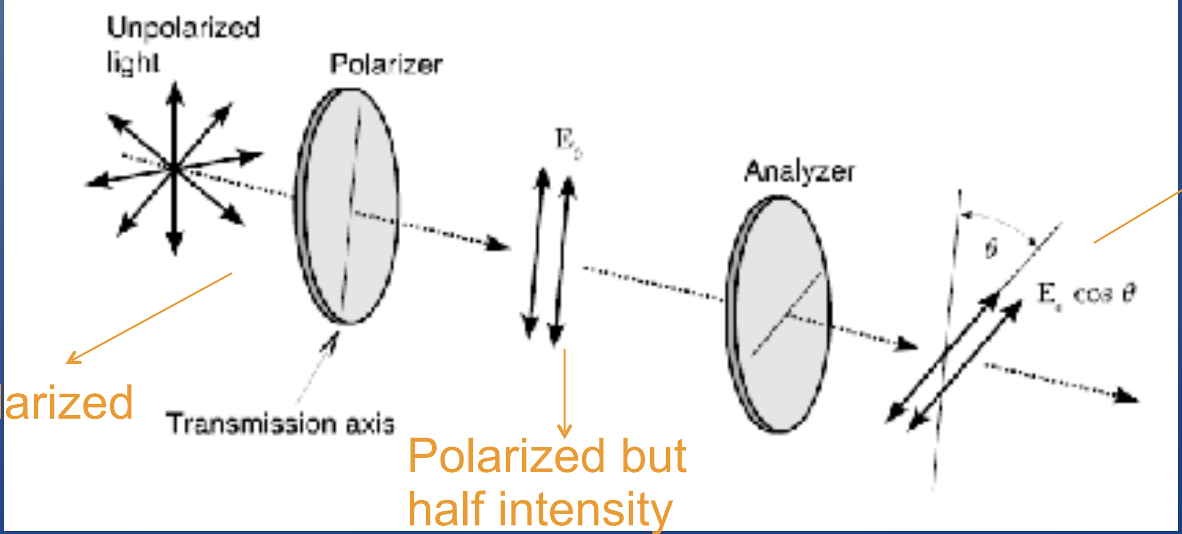


Unpolarized beam of light moving perpendicularly to the screen. No preferred direction of oscillation

Linearly polarized beam of light moving perpendicularly to the screen. Electric field points in one direction only.

Polarization by selective absorption

- White light (as from a light bulb) is usually *unpolarized*.
- **Polarizer** = material that selects one particular direction of oscillation of the incoming light
- If we place two linear polarizers in sequence then:
  1. First one: it makes unpolarized light linearly polarized
  2. Second one: it determines which fraction of the incoming light arrives at the end of the apparatus



Polarized and different intensity

Unpolarized

Polarized but half intensity

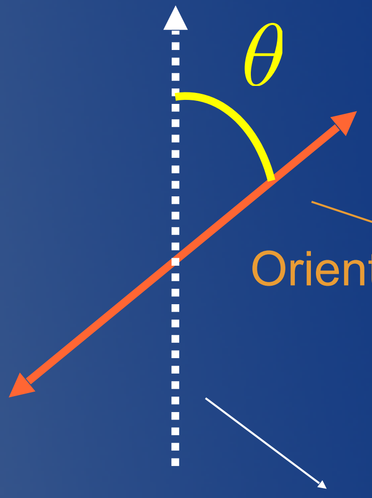
Malus' Law

- If we place two polarizers in sequence, the magnitude of the transmitted polarized electric field will depend on the angle between polarizers.

$$\left|\vec{E}_{\text{trans}}\right| = \left|\vec{E}_0\right| \cos\theta$$

Electric field coming out of second polarizer

Electric field coming out of first polarizer



Orientation of second polarizer

Orientation of first polarizer

- This is how the electric field behaves when passing through two linear polarizers. What do we actually see?

Malus' Law

- Our eyes cannot detect the electric field directly
- We only see its time average ⟶ intensity
- Intensity = magnitude squared of the electric field

$$I = \left|\vec{E}\right|^2$$

- From the formula in the previous slide we obtain the so-called ***Malus' Law***:

$$\boxed{I = I_0 \cos^2 \theta}$$

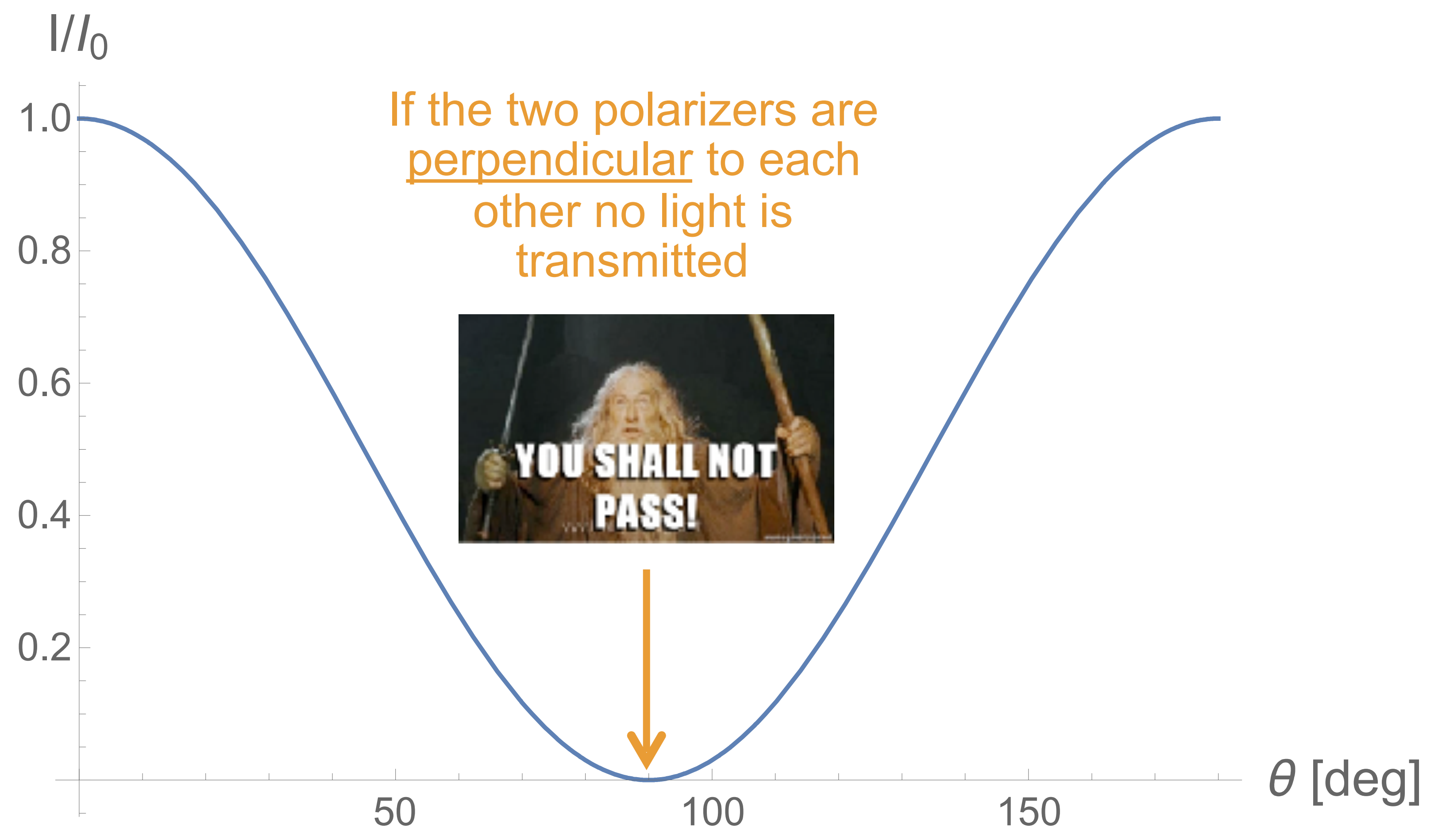
Intensity coming out of second polarizer

Intensity coming out of first polarizer

Relative angle between the axes of the two polarizers

Malus’ Law

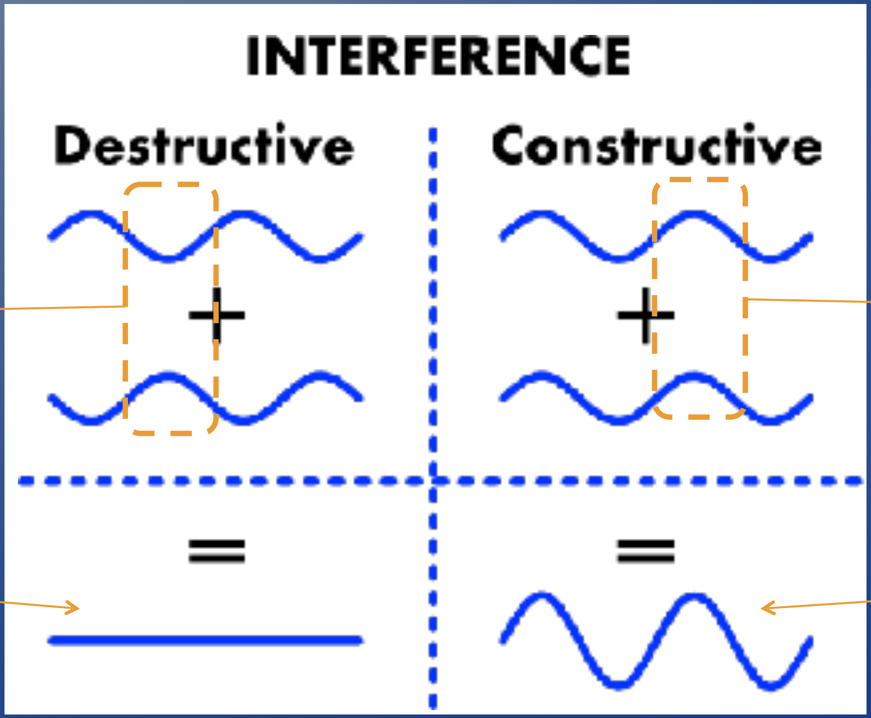
- The intensity coming out of the polarizers as a function of the angle between the two then looks like:



If the two polarizers are <u>perpendicular</u> to each other no light is transmitted

Interference

- An essential property of waves is the ability to get combined with other waves
- The result of this superposition can lead to a wave with greater or smaller amplitude
- This phenomenon is called interference



Maxima superimposed to minima

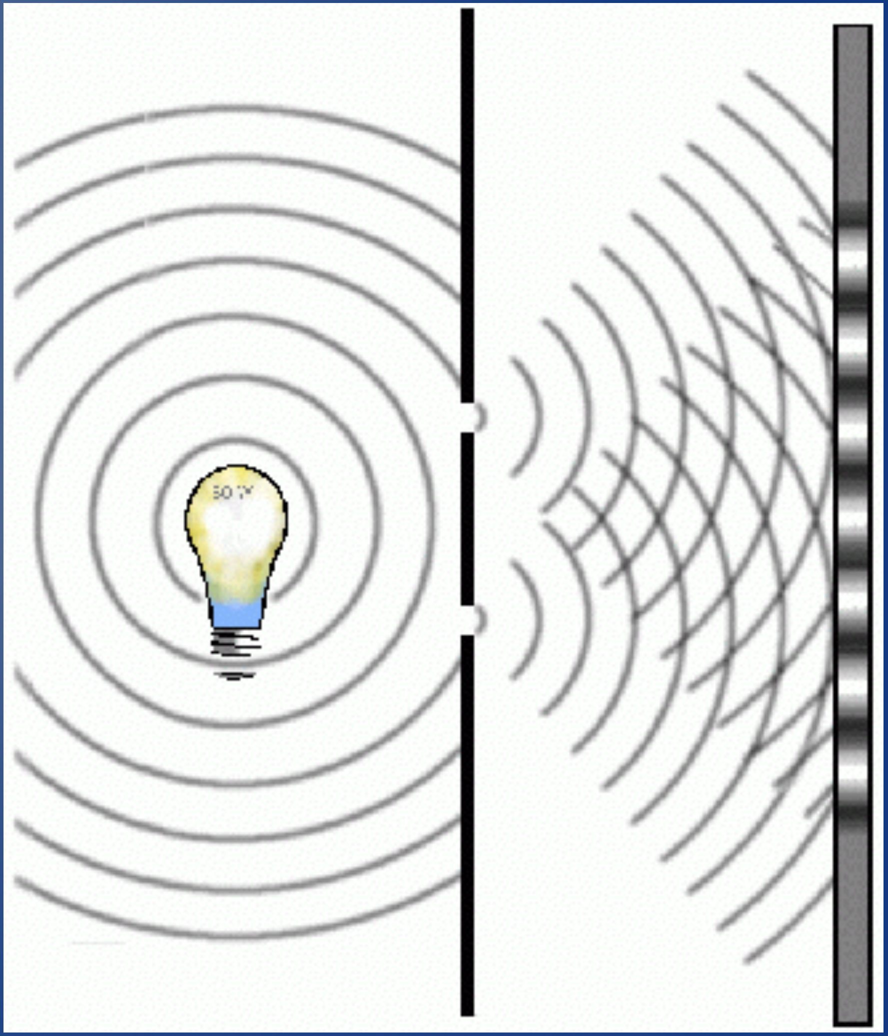
They cancel out

Maxima superimposed to maxima

They add to each other

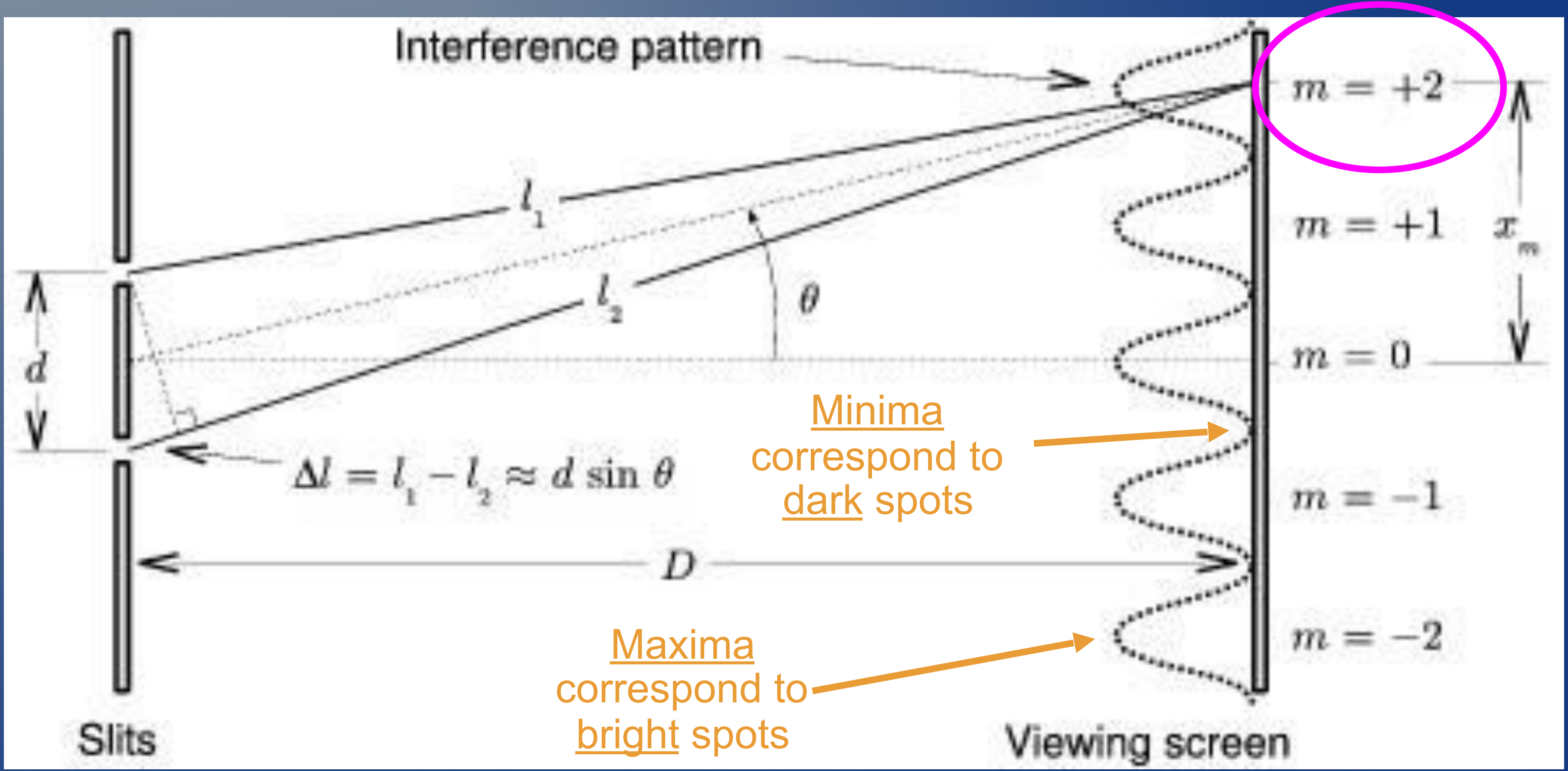
Young's double slit experiment

- **Question:** if light is a wave, what should we expect from it?
- Young's double-slit experiment (1801):
  - Pass light through two very narrow slits and observe pattern on distant screen.
  - Waves coming out of the two slits interfere and create a ***fringe pattern*** of bright and dark spots



Young's double slit experiment

- The pattern on the wall can be derived from optics
- We need to see how two rays from the two slits interfere with each other



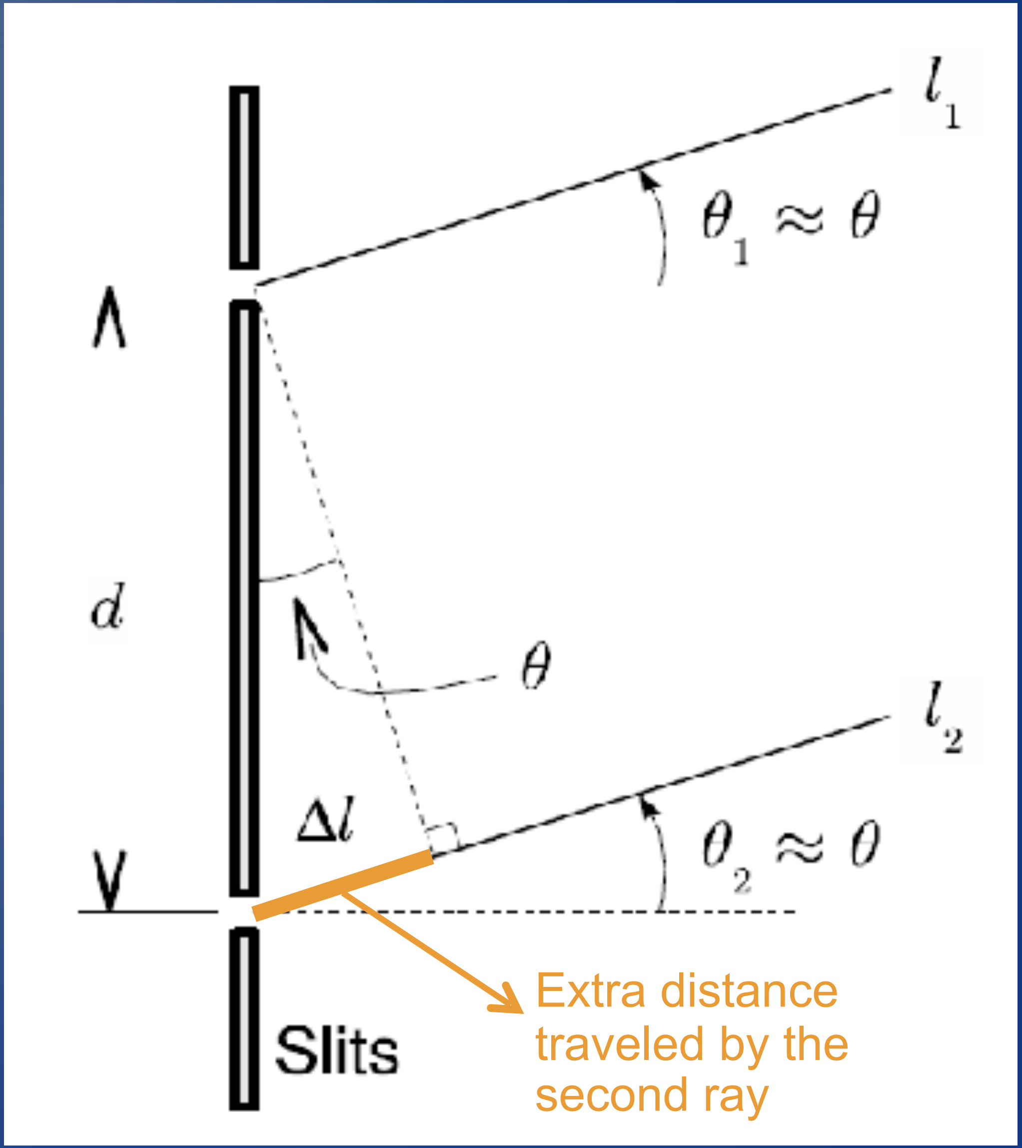
Minima correspond to dark spots

Maxima correspond to bright spots

Condition for a bright spot

- Let the screen be at a distance *D* from the slits. Let's take this distance much larger than the distance between slits (*D*>>*d*).
- Rays emerge almost parallel to each other.
- In order for both of them to end up on the same point (and hence interfere) one of the two must travel a slightly longer distance:

$$\Delta\ell = d\sin\theta$$



Extra distance traveled by the second ray

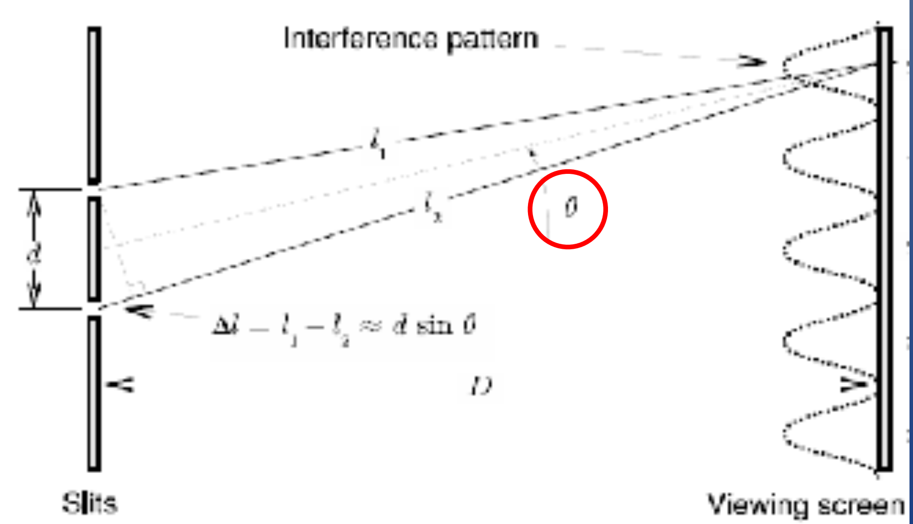
Condition for a bright spot

- We want a bright spot, *i.e.* constructive interference
- In order for two maxima to overlap the difference in travel distance must be a multiple of the wavelength

$$\Delta\ell = d\sin\theta = m\lambda$$

where *m* is an integer number and *λ* is the wavelength of incoming light

- Since *D>>d* we can use the small angle approximation:



$$\sin\theta \simeq \tan\theta \simeq x_m/D$$

The distance of the *m*-th bright spot from the center is then:

$$\boxed{x_m = m\left(\frac{\lambda D}{d}\right)}$$

Young's double-slit experiment

- The pattern appearing in the double slit experiment is due to the interference effect
- However, in real life you will also have **diffraction**. Light phenomena will always be a combination of the two effects

Young's double-slit experiment

- The pattern appearing in the double slit experiment is due to the interference effect
- However, in real life you will also have **diffraction**. Light phenomena will always be a combination of the two effects
- **Diffraction** = Spread of waves around an obstacle or slit
- Only relevant when the obstacle size is comparable to the wavelength
- Wave behaves as if it was interfering with itself

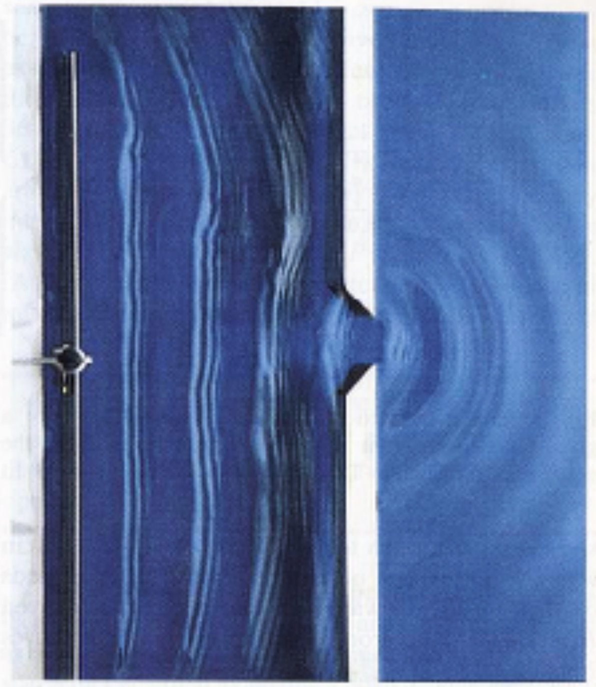


FIGURE 36-4 The diffraction of water waves in a ripple tank. Waves moving from left to right flare out through an opening in a barrier along the water surface.

Diffraction intensity pattern

- If diffraction is made around a single slit the intensity is given by:

$$I = I_0 \left(\frac{\sin\left(\frac{\pi a}{\lambda}\sin\theta\right)}{\frac{\pi a}{\lambda}\sin\theta} \right)^2$$

a = single-slit width
λ = wavelength
θ = angle on the screen

Diffraction intensity pattern

- If diffraction is made around a single slit the intensity is given by:

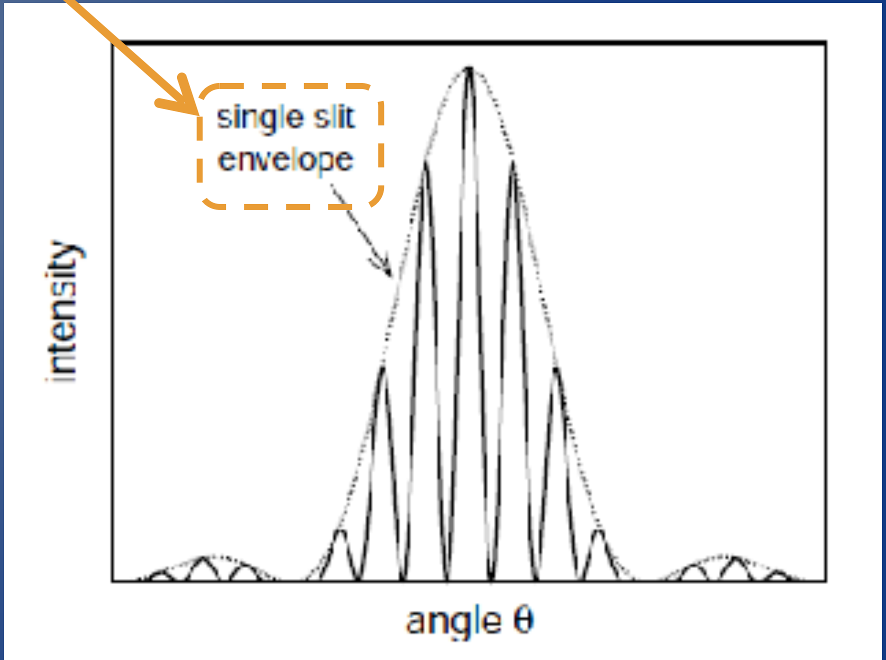
$$I = I_0 \left(\frac{\sin\left(\frac{\pi a}{\lambda}\sin\theta\right)}{\frac{\pi a}{\lambda}\sin\theta} \right)^2$$

a = single-slit width
λ = wavelength
θ = angle on the screen

- Single-slit ***minima*** occur at:

$$\frac{\pi a}{\lambda}\sin\theta = n\pi$$

$$n = \pm 1, \pm 2, \pm 3, \ldots$$



- Again, using small angle approximation, the minima occur at:

$$x_n = n\left(\frac{\lambda D}{a}\right)$$

Diffraction intensity pattern

- If diffraction is made around a single slit the intensity is given by:

$$I = I_0 \left(\frac{\sin\left(\frac{\pi a}{\lambda}\sin\theta\right)}{\frac{\pi a}{\lambda}\sin\theta} \right)^2$$

a = single-slit width
λ = wavelength
θ = angle on the screen

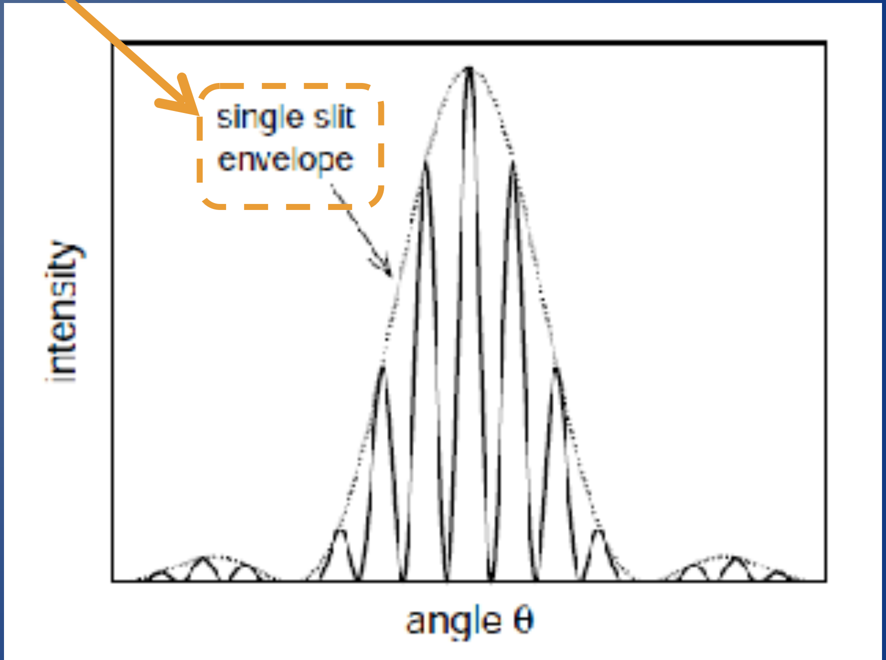
- Single-slit ***minima*** occur at:

$$\frac{\pi a}{\lambda}\sin\theta = n\pi$$

$$n = \pm 1, \pm 2, \pm 3, \ldots$$

- Again, using small angle approximation, the minima occur at:

$$x_n = n\left(\frac{\lambda D}{a}\right)$$



Careful! The expression is similar to that for the double slit but now it's for dark spots, not bright ones

The Experiment

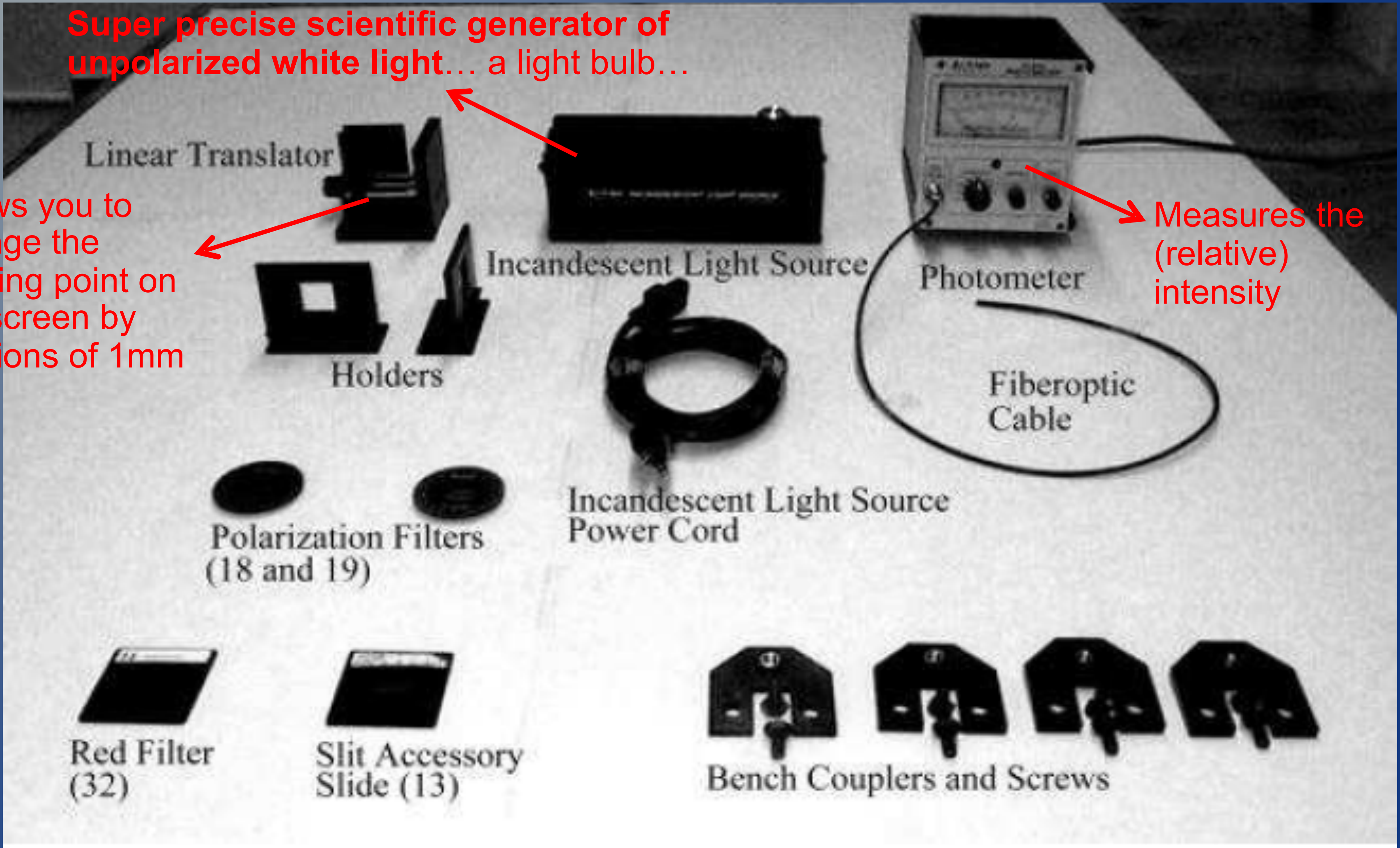
Goals

- To study the polarization properties of EM waves
  - Polarize a beam of white light
  - Verify **Malus' Law:** measure intensity of white light when light travels through two polarizers at an angle θ with respect to each other:

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

- To study the interference and diffraction phenomena
  - Use a He-Ne laser as coherent light source (single wavelength)
  - Determine λ of the laser from the double-slit ***interference*** pattern
  - Determine λ of the laser from single-slit ***diffraction*** pattern

Equipment



Super precise scientific generator of unpolarized white light… a light bulb…

Allows you to change the reading point on the screen by fractions of 1mm

Measures the (relative) intensity

Part 1: Malus' law

- **Equipment:**
  - Incandescent light source (source of EM waves)
  - Polarization filters
  - Photometer (measures intensity of outgoing EM waves)
- ***For polarization*:**
  - Incandescent light is a source of **unpolarized** EM waves
    - E-field has no preferred direction
  - Place a polarizer in front of the incandescent light source

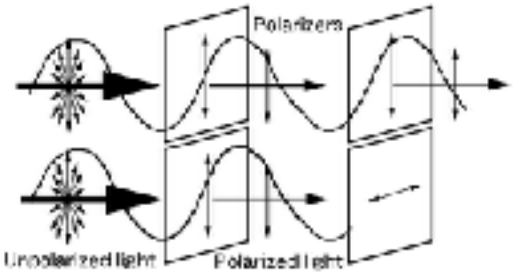
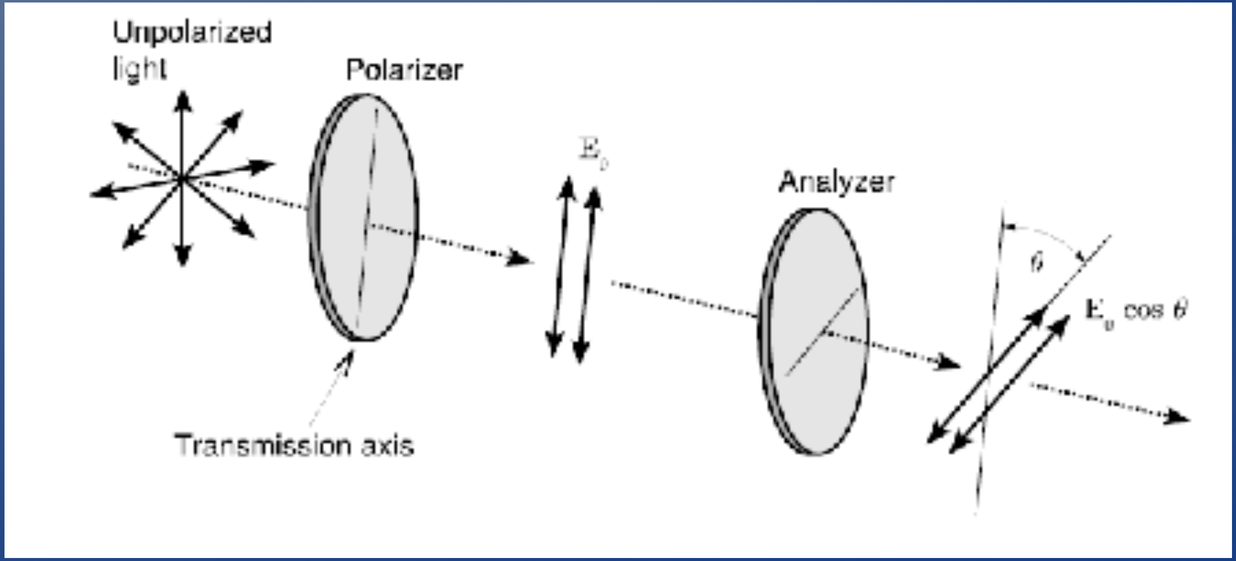


Fig.1 Polarization of light

Outgoing light should be polarized!

Part 1: Malus' Law

- Polarizers in sequence
  - Place two polarizers in front of the light source
- Measuring intensity of light:
  - Align the axis of both polarizers such that they are ***parallel*** to each other. Measure and record intensity.
  - Rotate the second polarizer in 5-10 degree increments with respect to the first one. Record intensity at each step

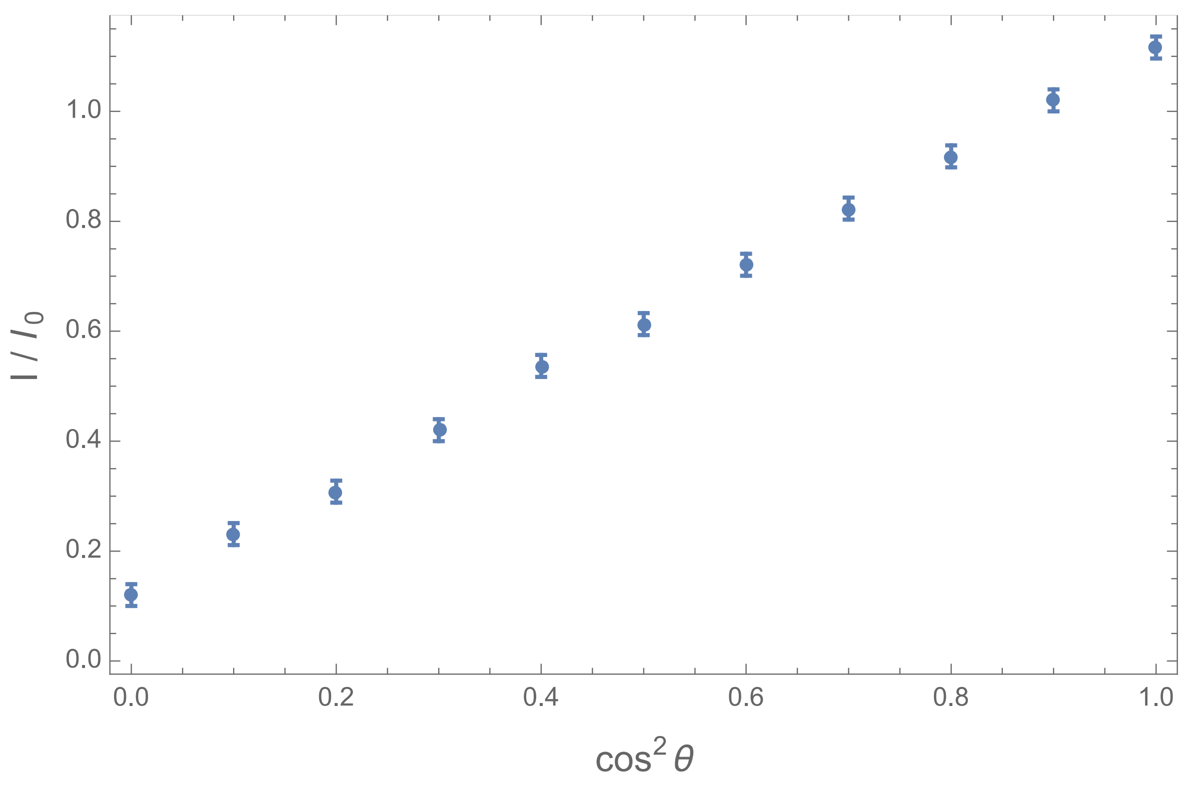


Part 1: Malus' Law

- According to Malus' law:

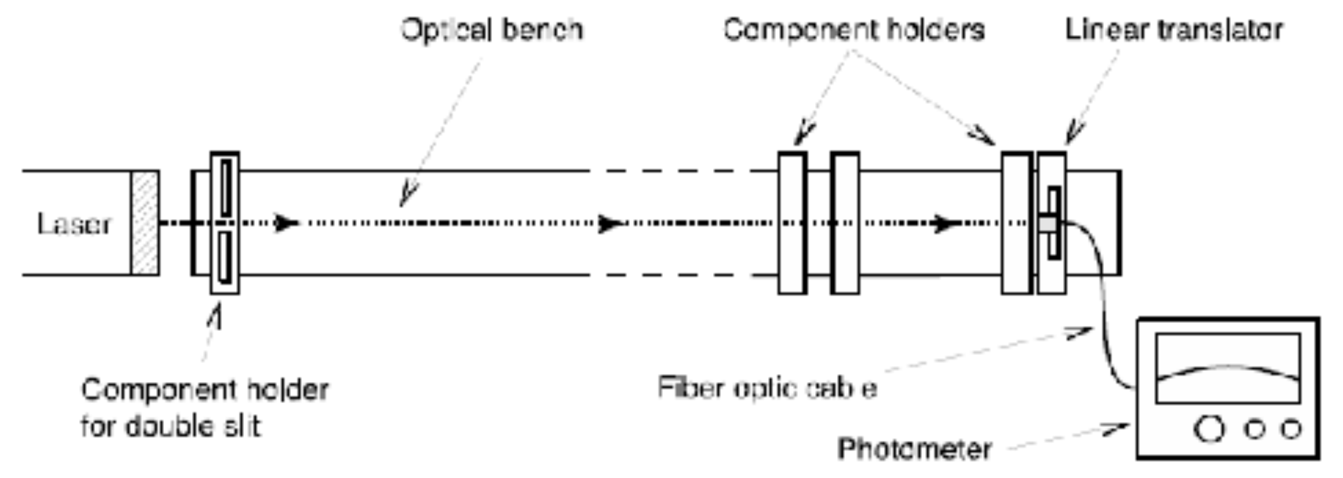
$$I(\theta) = I_0 \cos^2 \theta$$

- You will have a set of (I_i, θ_i)pairs
- Linearize the data by plotting I/I_0 vs. $\cos^2 \theta$
- Perform a linear fit and find slope and intercept (w/ errors!). Are they what you expect?
- Plot residuals to check for consistency of the fit



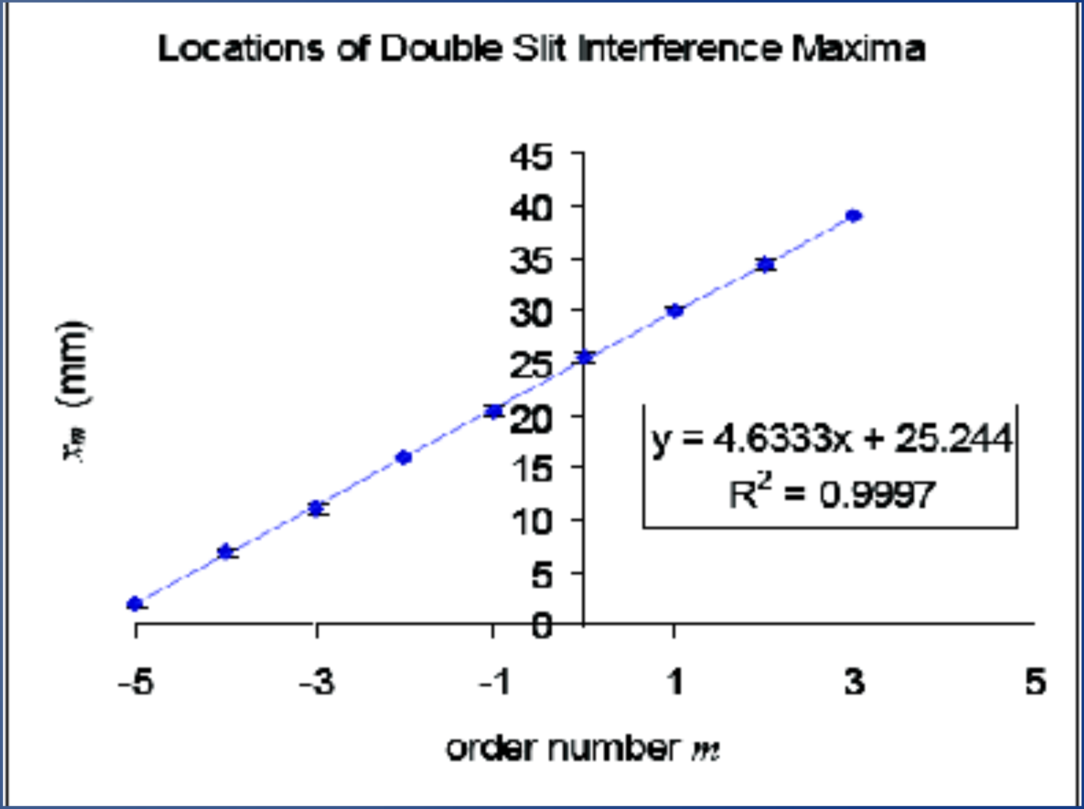
Part 2: double-slit experiment

- Procedure:
  - Mount laser in far end of optical bench.
  - Mount slit set C (double-slit) in front of the laser beam.
  - Observe double-slit intensity pattern with a white piece of paper.
  - Use ***linear translator with fiber optic*** attached to measure intensity at different positions in the transverse direction



Part 2: double-slit experiment

- Record the position of maxima
- Plot x_m vs. order number (m)
- Perform a linear fit
- Use slope to estimate the wavelength of the laser
  - Remember to **propagate uncertainties**!
- If you are careful enough the results can be fairly accurate:



$$\lambda_{\text{meas}} = 626.1 \pm 3.5 \text{ nm}$$

$$\lambda_{\text{theor}} = 632.8 \text{ nm}$$

Part 3: single-slit envelope

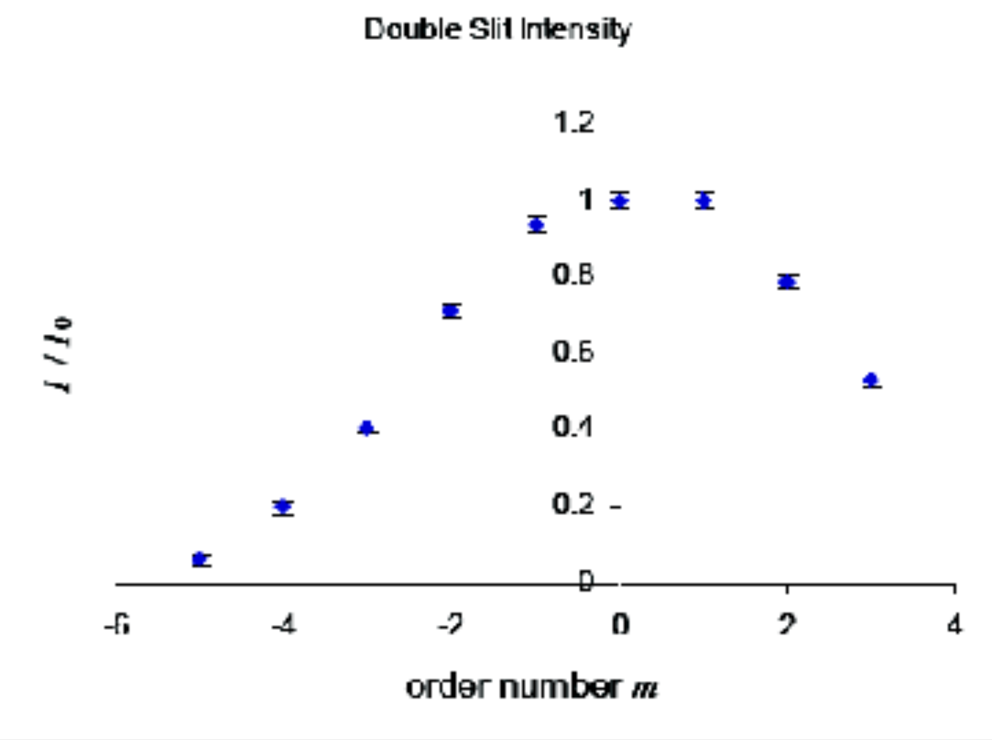
- Once again take measurements in the transverse direction but in smaller increments and look for brighter spots

- Plot relative intensity (*I/I_o*) vs. order number *m*.

- Should be able to observe the single-slit envelope.

- Using the ***single-slit width*** (*a*), determine wavelength of laser.

$$I = I_0 \left(\frac{\sin\left(\frac{\pi a}{\lambda} \sin\theta\right)}{\frac{\pi a}{\lambda} \sin\theta} \right)^2$$

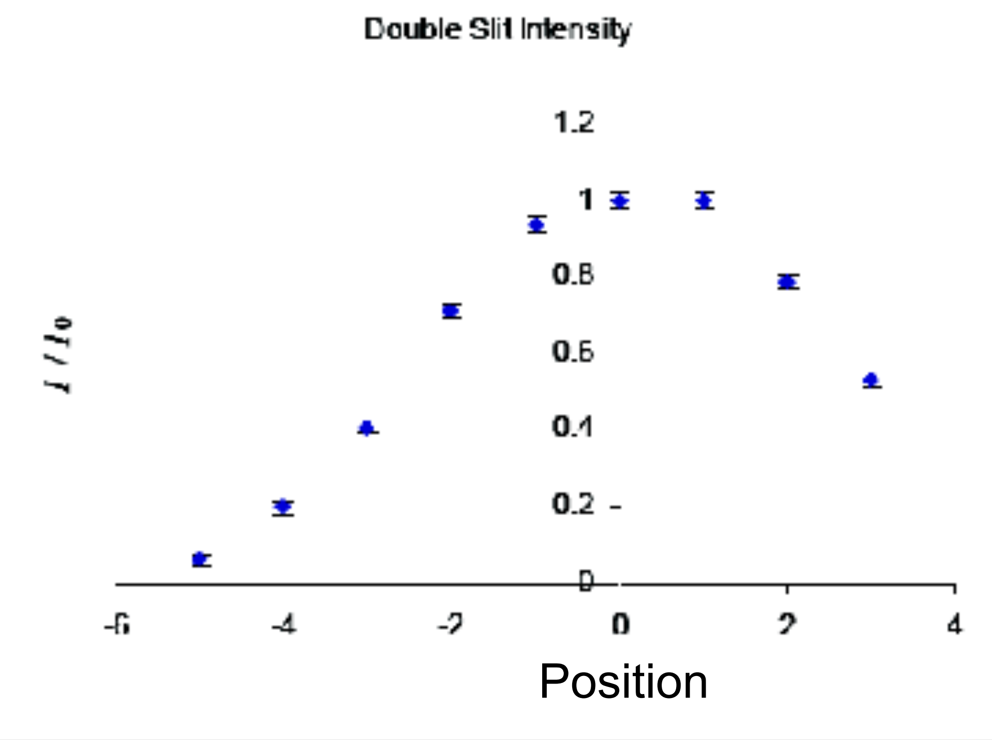


IMPORTANT: For this part of the experiment switch to ***slit D***!

Part 3: single-slit envelope

- Once again take measurements in the transverse direction but in smaller increments and look for brighter spots
- Plot relative intensity (I/I_o) vs. position x_m.
- Should be able to observe the single-slit envelope, note where the single slit minima are x_n
- Plot x_n vs. n, where n is minima order number
- Using slope and wavelength from part 2, determine a

$$x_n = n\left(\frac{\lambda D}{a}\right)$$



NOTE: This part may vary depending on your TA. Ask them for the exact procedure!

IMPORTANT: For this part of the experiment switch to ***slit D***!

Tips

- Here are some tips that might be useful:

  1. For all the three parts: be careful when you read the intensity. The photometer is analogical and the reading might be influenced by parallax. Try to read the photometer always in the same way
  2. For the polarizer part: put the polarizers as close as possible to the optic fiber cable to minimize the amount of environmental light coming in.
  3. For the last part: move everything closer to the laser to make the pattern bigger but remember to change the value of *D*!