Lab 16

Wave-Particle Duality

Continuing Objectives

4. Be able to make careful measurements to ensure reproducible results.

5. Know how to keep a clear and organized record, including an introduction (with purpose of lab and appropriate laws or equations), apparatus sketch, table of raw data and calculated quantities, and a good conclusion or summary.

6. Be able to make a good graph, either in your notebook or with a computer, including labels, scales, units, dependent, and independent variables.

Introduction

Here you will study the interference of light at very low light levels in a two-slit experiment. As shown in Figure 16.1, light from a lamp passes through a thin entrance slit, through a green filter, and then through a double slit. Individual photons are detected by a photomultiplier tube (PMT) approximately a meter away.

Just in front of the double slit is a slit cover that you can slide back and forth to cover either one of the slits or neither. The PMT, which has another narrow slit in front of it, can be moved from side to side with a micrometer. The light arriving at the PMT is extremely faint with at most a few thousand photons arriving per second.

The PMT converts each photon of light that passes through the detector aperture into a brief pulse of electric current by the following sequence of steps. A photon first ejects a single electron (via the photoelectric effect) from a photosensitive electrode called a cathode. This electron is then accelerated by an electric field and slams into another electrode called a dynode, from which it ejects two or three secondary electrons. These electrons, in turn, slam into yet another dynode, thus further multi-

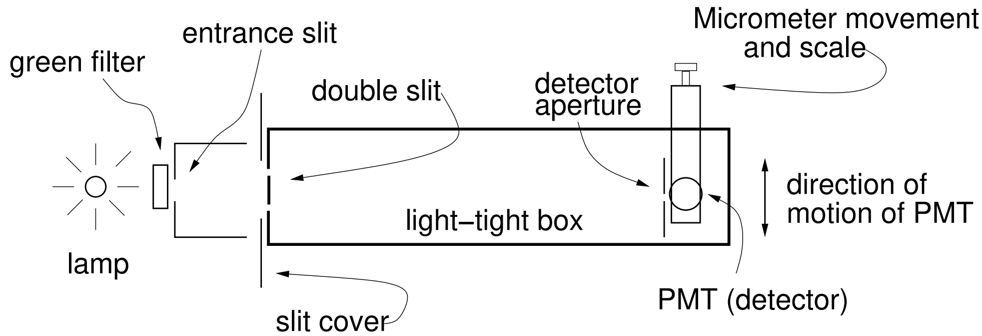


Figure 16.1: Top view of optical set-up.

plying the burst of electrons. After several such stages of amplification, the electron burst may contain as many as 10^4 electrons.

When this burst is collected by an anode and sent along a wire to the oscilloscope it produces a noticeable deflection on an oscilloscope. (10^4 electrons $\times$ 1.6 $\times$ 10^{-19} coulombs per electron $\div$ 10^{-8} sec is a current of 0.16 μA.; this current yields, after further modification, a signal of approximately 2 V.) You will move the PMT along the direction shown in the figure and graph the photon count rate vs. position, for four situations: (1) slit 1 open with slit 2 closed; (2) slit 2 open with slit 1 closed; (3) both slits open; and (4) both slits closed.

What do you expect to see? For example, suppose you fix the PMT location and measure the photon rate in all four situations. (Note that the background rate with both slits closed is **not** zero because of random thermal emission of electrons from the cathode surface inside the PMT). Let BG represent the background rate with both slits closed,and R_1 and R_2 the rates for photons arriving at the detector when either slit 1 or slit 2, respectively, is open. Then classically you might expect the following.

Slit cover position	Counting rate
slit #1 open	$N_1 = BG + R_1$
slit #2 open	$N_2 = BG + R_2$
both slits open	$N_{12} = BG + R_1 + R_2$
neither slit open	BG

But let's do the experiment and observe what happens.

Procedure

Part I: Electronics

WARNING: This apparatus requires careful optical alignment and electronic adjustments. Be sure to NOT disturb the lamp and DO NOT make any adjustments to the oscilloscope and counter-timer.

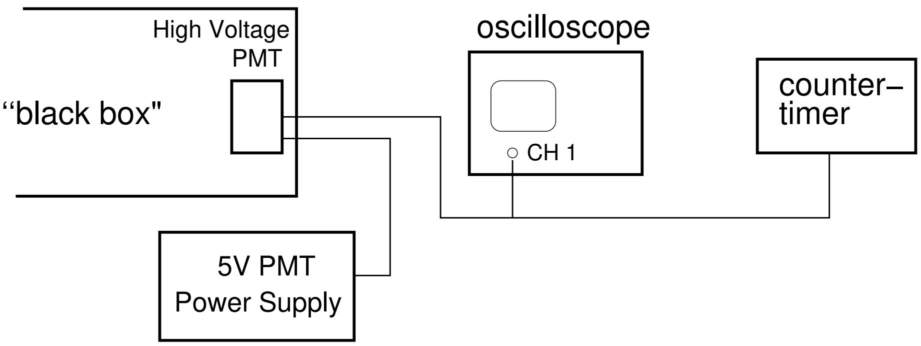


Figure 16.2: Block diagram of electronic set-up

The PMT uses the photoelectric effect and turns the arrival of one photon into an electrical voltage pulse that we can observe on the oscilloscope and count with the counter.

1. Make sure the lamp is unplugged.

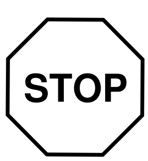
2. Turn on the power strip located on your bench. It powers the oscilloscope and the counter-timer. **DO NOT** turn on the power to the PMT power supply yet.

   Do not ever open the trap doors all the way with the PMT power on. You WILL damage the PMT.

3. Make sure that both trap doors on top of either end of the large black box are closed. **NOW**, turn on the PMT power supply.

4. With the photomultiplier tube on, you should now see pulses on the oscilloscope. Note, on the bottom of the screen of the oscilloscope it shows that the time per division is set to 500 ns/div. This means each block on the horizontal axis corresponds to 500 ns. The vertical axis corresponds to voltage. Therefore, the sharp peaks you see correspond to very rapid pulses.

5. **Slightly** open the trap door nearest the lamp end of the box to let *just a little* light in (see warning above). Verify that you can see more frequent pulses on the oscilloscope and the pulse counter displays larger numbers. Each pulse signals the arrival of one photon at the cathode of the PMT.



Based on your observations so far, would you conclude that light is a particle or a wave? Discuss with your partner and write your conclusions in your lab notebook. Then, discuss your results with your instructor or TA.

6. The counter-timer should be on. Verify that the Gate time is set to 1.0 sec and the GATE REP RATE should be set to the 12 o'clock position. This is the

background counting rate, BG.
Note: In all counting experiments the number of counts in a fixed time interval is subject to fluctuations. In the *Radioactive Decay* lab, you will learn that when counts occur randomly (following so called Poisson statistics), as in this experiment, the standard deviation of the number of counts obtained in many repetitions is equal to the square root of the average number of counts. For example, if you get about 64 counts on the average with the detector at a certain position, you can expect fluctuations on the order of ± 8 counts when you repeat the measurement.

Part II: Puzzles and Predictions

You will want to quickly determine whether your apparatus is set up properly before taking any extensive data. Also, you should make some measurements and predictions to provide a hint of the wave-particle duality paradox. You'll make careful and more extensive measurements in the final part of this lab.

1. Illuminate the slits by plugging in the lamp. Make sure that the green filter is in place such that the light that falls on the slits has passed through the filter first. You should notice that your count rate has increased, along with the number of pulses (with the black or white card removed).

2. To cover just one slit, **gently** push the slit cover all the way to one side. To cover just the other slit, **gently** push the slit cover all the way to the other side. To have both slits open, **gently** push the slit cover to some position between the previous two cases. To cover both slits, use the index card (gently).

   In the next step, you will be asked to move the detector to its extreme left and extreme right positions. **The detector cannot reach the lower limit 0 and the upper limit 30 mm of its range**. DO NOT ATTEMPT TO TURN IT BEYOND ITS NATURAL RANGE.

3. With **BOTH SLITS OPEN**, move the detector all the way to one end by turning the knob on the micrometer at the end of the box opposite the lamp/slit end. Do not turn the knob beyond its natural extension. Observe the count rate on the counter as you turn the knob to move the detector. Note that this part is just a quick check to make sure the apparatus is set up properly, so you do not need to record this data very carefully - just keep track of trends.

4. Start moving the detector to the other side by turning the knob. Remember that the timer is counting for one second, so wait at least one second before moving the detector again. Observe the count rate. As you move the detector from one end to the other, you should notice that the count rate goes up, then goes back down, then goes back up, several times. This fluctuation should be beyond the fluctuation you would expect with just standard counting fluctuations and

Poisson statistics. If you don't get this behavior or you're not sure, call an instructor or TA over to your lab station.

5. After observing this oscillatory increase and decrease in count rate, move the detector to a position near the middle of the detector position range. Move the detector in either direction until you come to the first region where the count rate is low. Call this count rate N_{both}: the count rate with both slits open. Record N_{both} in your notebook.

6. Now, keep the detector at the **same** position and **gently** slide the slit cover all the way to one side (thus having **just** Slit #1 open, and Slit #2 closed). To keep the slit cover in this position use the rubber band. Observe the count rate. Call this count rate N_1: the count rate with just Slit #1 open. Record N_1 in your notebook.

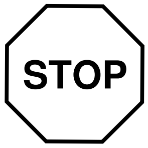
7. Still keep the detector at the **same** position. Now, detach the rubber band and **gently** slide the slit cover all the way to the other side (thus having **just** Slit #2 open, and Slit #1 closed) and again use the rubber band to keep the slit cover in this position. Observe the count rate. Call this count rate N_2: the count rate with just Slit #2 open. Record N_2 in your notebook.

8. Consider the sum of $N_1 + N_2$, (the count rate with just Slit #1 open plus the count rate with just Slit #2 open) and compare it to N_{both} , (the count rate with Slit #1 **and** Slit #2 open). Does this result make sense to you? Is anything strange about this result?

9. Now consider N_1 and N_2 as the detector position is varied. These can be illustrated via graphs whose vertical axes represent the number of counts and whose horizontal axis the detector position. Assuming that light is a stream of particles and that only Slit #1 is open, predict and (qualitatively) graph N_1 vs. detector position. Make a similar prediction and graph, using the same axes, assuming that only Slit #2 is open.

10. If light behaved as a classical *particle* in this part of the experiment, the intensity pattern with both slits open would look like the sum of your sketches in the previous part (be able to explain why). Sketch the pattern you would expect to see if light acted like a classical particle.

11. If light behaved as a classical *wave* in this part of the experiment, the intensity pattern with both slits open would look very different from that you would obtain if light acted like classical particles. Sketch the pattern you would expect to see if light acted like a classical wave.



Discuss your results and predictions with your instructor or TA before proceeding to Part III.

Part III: Measurement of Intensity Patterns

Take data for a set of four graphs (all on the same set of axes) of count rate vs. detector position over the range of approximately 5-25 mm. Use the Excel template `WavePartice_template.xlsx` which is located in the public netspace folder `PHYS 211_212 Lab` ⟶ `212Lab` ⟶ `Wave Particle Duality`. This template organizes your data into four data sets (for different slit cover positions.) **Before you continue**, read the following three suggestions which will save you some time:

- For the graph of data with both slits open, take a reading every half mm over the full range of micrometer movement. For the two graphs with just one slit open, take a reading every mm. And finally, for the graph of the background rate (with both slits closed), just take a reading every 2 mm.
- The Excel template will plot each graph as you take the data, so that you can see the shapes of the curves as they develop. As you are taking data, compare your graphs to your previous predictions. Have an instructor or TA look over your data as well to make sure you are in good shape.
- **Take the curve with both slits open first, since it should have the highest count rates.** To establish the vertical axis of your graph, make a fairly quick scan of the detector position (with both slits open) and notice the maximum count rate. Make sure that your graph uses a full page in your notebook.

Questions

Write answers to the following questions in your lab notebook.

1. What aspect(s) of this experiment would lead you to believe that light is a particle?
2. What aspect(s) of this experiment would lead you to believe that light is a wave?
3. Does light behave as a wave or a stream of particles in this experiment? Give reasons for your answer based on observations you have made.
4. Let's say that we believe in the model describing light as a stream of particles, (photons). Let's perform the following simple calculations and try to interpret

the results.

(a) Consider having both slits open. The entire apparatus, from slits to detector, is about a meter in length. Determine how long it takes for a single photon to travel this length.

(b) Check your data to determine the largest count rate you obtained at any of the detector positions.

(c) Using this maximum count rate, estimate the average time between the arrival of photons at the detector (Hint: think about units).

(d) Compare the photon travel time from part (a) to the estimated time between photons from part (c). It may help to think about how often the apparatus is *empty* when the lamp is on.

(e) Based on the previous step, estimate how many photons at MOST are in the apparatus at any given time.

(f) A possible explanation for the interference pattern observed when both slits are open is the interference of one photon going through one slit with *another* photon going through the other slit. Does your result from the previous step support this? Explain.

Write a conclusion for this lab.