Assembly Instructions for TeachSpin's Two-Slit Apparatus

"Two-Slit Interference, One Photon at a Time" is shipped in two boxes. The long thin box holds a black aluminum **U-channel** with two wooden feet, The other box contains these instructions, the red binder containing the Manual, a package of cables, the "**AMPLIFIER MODULE**", the **Pulse Counter/Interval Timer (PCIT)**, and **two universal power supplies**.

1. Unpack the U-channel and the AMPLIFIER MODULE parts of the apparatus, and note that each has a black circular flange. You will see an O-ring held in place by a strip of tape in the flange attached to the U-channel. Remove the tape, but leave the O-ring in its groove.

2. From the AMPLIFIER MODULE, loosen the four socket-head cap screws which hold in place the silver shipping cover. Save the four screws, and set aside the shipping cover.

   Do not touch or damage the photodiode detector that is visible at the center of the circular flange on the back of the AMPLIFIER MODULE. (Fig. 1)

   Making sure the O-ring stays in its groove, attach the AMPLIFIER MODULE to the U-channel by mating the two circular flanges. Insert the four screws you saved through the four holes in the flange on the U-channel, and into the threaded holes in the flange on the AMPLIFIER MODULE. (See illustration on the attached page.)

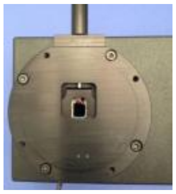


Fig. 1 Circular Flange on back of AMPLIFIER MODULE

3. When all four screws are engaged, tighten them in stages until the O-ring is compressed uniformly around its circumference. You need a light-tight, but not a vacuum-tight, seal here.

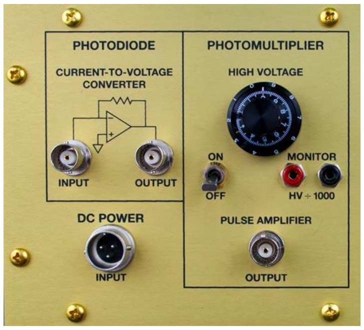


Fig. 2 AMPLIFIER MODULE

4. Cabling

   a. Put the assembled unit down onto its wooden feet. Find the thin cable coming from the top of the circular flange on the AMPLIFIER MODULE. Connect its BNC plug to the INPUT jack of the CURRENT-TO-VOLTAGE CONVERTER on the front panel of the AMPLIFIER MODULE (Fig. 2).

   b. Find the long cable emerging from underneath the circular flange on the AMPLIFIER MODULE, and connect the 2-pin plug on its far end to the connector labeled ALARM on the brass panel at the far end of the U-channel (Fig. 3).

Fig. 3 Brass panel on U channel

   c. Find the long grey cable which has a 3-pin connector on both of its ends. Connect one end of it to the DC OUTPUT connector on the brass panel at the far end of the U-channel, and the other end of it to the DC POWER INPUT connector on the front panel of the AMPLIFIER MODULE.

   d. Find the two small 'universal power supplies' and ***note their labels***! The Two-Slit power supply has +15 V output. The +5 V output is for the PCIT.

   DO NOT connect the +15-V supply to the PCIT. Using the wrong power supply will damage the Counter.

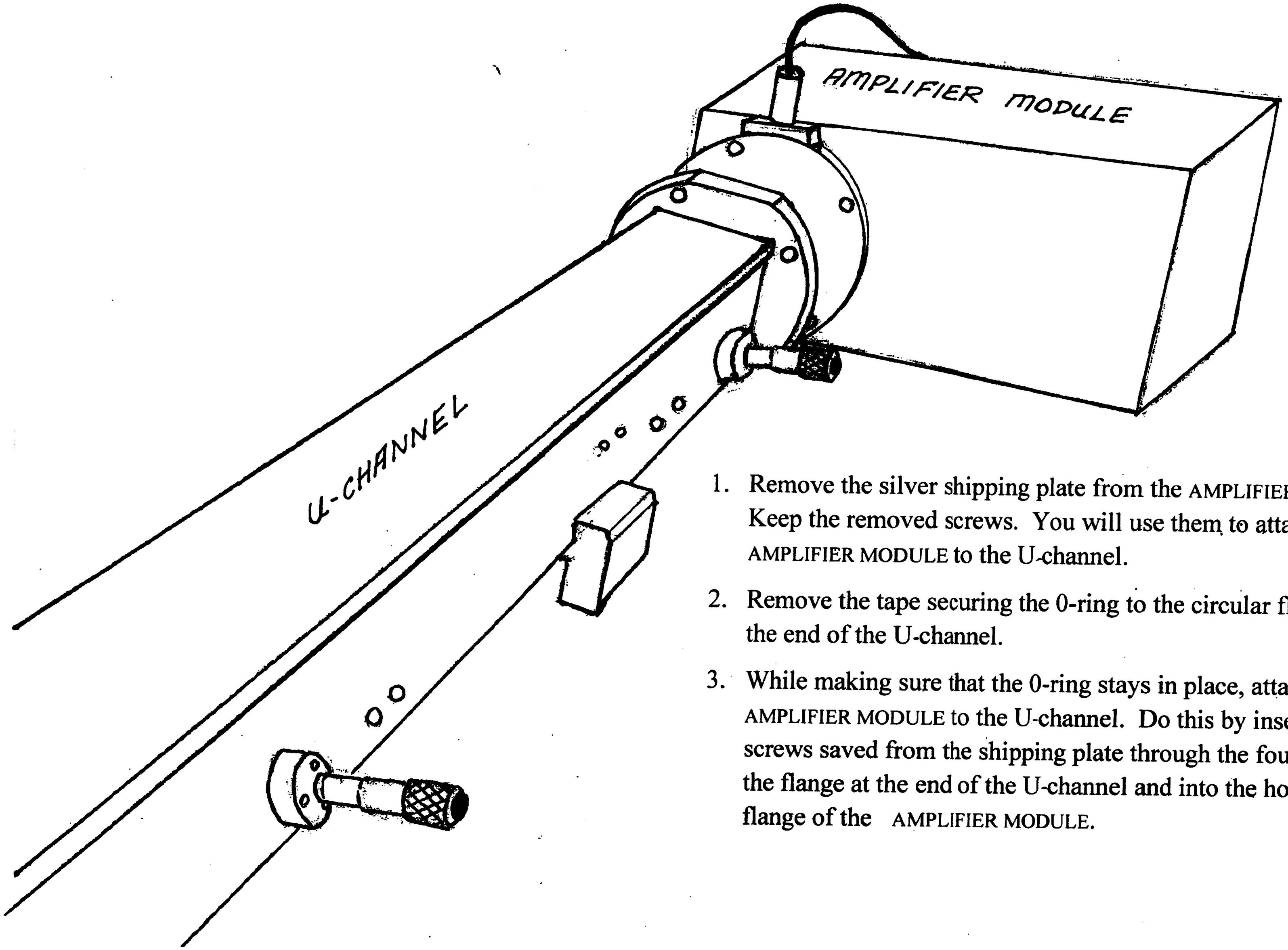
   Attach the output plug of the +15 V supply to the DC INPUT connector on the brass panel at the far end of the U-channel (Fig. 3). Now connect a line cord to this power supply. The +5 V supply will be used with the PCIT Counter/Timer unit.

   f. Note that there is, at this point, no connection to the LASER MOD(ulation) BNC input on the brass panel on the far end of the U-channel. Nor is there, as yet, anything connected to the two OUTPUT BNC connectors on the AMPLIFIER MODULE.

TEACH SPIN

Instruments Designed for Teaching

TWO SLIT ASSEMBLY DIRECTIONS



1. Remove the silver shipping plate from the AMPLIFIER MODULE Keep the removed screws. You will use them to attach the AMPLIFIER MODULE to the U-channel.
2. Remove the tape securing the 0-ring to the circular flange at the end of the U-channel.
3. While making sure that the 0-ring stays in place, attach the AMPLIFIER MODULE to the U-channel. Do this by inserting the screws saved from the shipping plate through the four holes in the flange at the end of the U-channel and into the holes on the flange of the AMPLIFIER MODULE.

TEACH SPIN

Instruments Designed for Teaching

TWO-SLIT INTERFERENCE, ONE PHOTON AT A TIME

"The Essential Quantum Paradox"

Instruction Manual

TWS2-A

A Product of TeachSpin, Inc.

TeachSpin, Inc.   2495 Main Street   Suite 409
Buffalo, NY   14214-2153
(716) 885-4701 or www.teachspin.com

TeachSpin Instruction Manuals
Two-Slit Interference, One Photon at a Time (TWS2-A)
Pulse Counter/Interval Timer (PCIT1)

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Chapter 1. Conceptual and Historical Introduction

A. Wave-particle duality

Pick up any book about quantum mechanics and you're sure to read about ‘wave-particle duality’. What is this mysterious ‘duality’, and why should we believe that it’s a feature of the real world? This manual describes the TeachSpin Two-Slit apparatus designed to make the concept of duality as concrete as possible, by letting you encounter it with photons, the quanta of light.

This apparatus makes it possible for you to perform Young’s famous two-slit interference experiment with light, even in the limit of light intensities so low that you can record the arrival of *individual photons* at the detector. And that brings up the apparent paradox that has motivated the concept of duality: In the very interference experiment that makes possible the measurement of the wavelength of light, you will be seeing the arrival of light in particle-like quanta, in individual photon events. How can light INTERFERE like waves and yet arrive as particles? This paradox has been used, by no less an authority than Richard Feynman, as the introduction to the fundamental issue of quantum mechanics:

> “In this chapter we shall tackle immediately the basic element of the mysterious behavior in its most strange form. We choose to examine a phenomenon which is impossible, *absolutely* impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the *only* mystery. We cannot make the mystery go away by explaining how it works. We will just *tell* you how it works. In telling you how it works we will have told you about the basic peculiarities of all quantum mechanics.” [R. P. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics*, vol. I, ch. 37, or vol. III, ch. 1 (Addison-Wesley, 1965)]

You should find and read either of these famous chapters in the *Feynman Lectures* that introduce the central features of quantum mechanics using the two-slit experiment as an example. Feynman notes that he discusses the experiment as if it were being done with particles with rest mass, such as electrons. He also wrote in an era in which he was discussing a ‘thought experiment’. But since that time, the two-slit experiment really has been done with neutrons [see *Reviews of Modern Physics* **60**, 1067-1073 (1988)]. In performing Two-Slit Interference, One Photon at a time, you too will translate a thought experiment into a real one, in this case with photons.

There are several technical advantages to the use of photons of visible light. They are easily produced and readily detected *as individual events*, using the ordinary tools of optics. They propagate freely in air and require no vacuum system. They are electrically neutral, and thus interact neither with each other nor with ambient electric and magnetic fields. They are (at high enough levels) directly visible to the eye. Finally, their wavelengths are of a much more convenient size than the available wavelengths of electrons or neutrons. All these technical advantages make it possible to perform even the single-photon version of the two-slit experiment in a tabletop-sized and affordable instrument.

B. Historical context

There is a rich historical background behind the experiments you are about to perform. You may recall that Isaac Newton first separated white light into its colors and, in the 1680's, hypothesized that light was composed of 'corpuscles', supposed to possess some properties of particles. This view reigned until the 1800's, when Thomas Young first performed the two-slit experiment now known by his name. In this experiment, he discovered a property of *destructive interference*, which seemed impossible to explain in terms of corpuscles, but which is very naturally explained in terms of waves.

Young's experiment not only suggested that such 'light waves' existed, it also provided a numerical result for the wavelength of light, measured in familiar units. (He even showed that the measured wavelength correlated with the subjective color of the light used.) Light waves became even more acceptable with dynamical theories of light, such as Fresnel's and Maxwell's, in the 19th century, until it seemed that the wave theory of light was incontrovertible.

The discovery of the photoelectric effect, and its explanation in terms of light quanta by Einstein, threw the matter into dispute again. The explanations of blackbody radiation, of the photoelectric effect, and of the Compton effect seemed to point to the existence of 'photons', quanta of light that possessed definite and indivisible amounts of energy and momentum. So successful have these models become that the modern 'photon' or quantum-of-light might seem to be Newton's corpuscle brought back to life.

The difficult thing to realize is that, whatever light might actually be, it *still* displays all those phenomena which gave support, in the 19th century, to wave interpretations. *That is to say, even if light is 'composed of' photons, it still displays Young's two-slit interference phenomena*. So does light have a dual nature, of waves and of particles? And if experiments force us to suppose that it does, how does the light *know* when to behave according to each of its natures? These are the sorts of questions that lend a somewhat mystical air to the concept of duality.

Of course, the deeper worry is that the properties of light might be not merely mysterious, but in some sense self-contradictory. You will be confronted with just the sort of evidence which has led some scientists to worry that our theories for light, or at least our pictures of light, are not only surprising but also inconsistent or incoherent. As you explore the phenomena, keep telling yourself that *the light is doing what light does naturally*. And keep on asking yourself if the difficulties lie with light, or with our theories of light, or with our verbal, pictorial, or even mechanical interpretations of these theories.

C. Goals for this apparatus

It is the purpose of this experimental apparatus to make the phenomenon of light interference as concrete as possible, and to give you the hands-on familiarity which will allow you to confront duality in a precise and definite way. When you have finished, you might not fully understand the *mechanism* of duality – Feynman asserted that nobody really does – but you will certainly have direct experience of the actual phenomena that motivate all this discussion.

Here, then, are the goals of the experiments that this apparatus makes possible:

1. You will be seeing two-slit interference *visually*, by opening up an apparatus and seeing the exact arrangements of light sources and apertures which operate to produce an 'interference pattern'. You'll be able to examine every part of the apparatus, and make all the measurements you'll need for theoretical modeling.
2. You will be able to perform the two-slit experiment *quantitatively*. In addition to recreating Young's measurement of the wavelength of light, you will get detailed information about light intensities in a two-slit interference pattern that can be compared to predictions of wave theories of light.
3. You will be able to perform the two-slit experiment *one photon at a time*, continuing the same kind of experiments, but now at a light level so low that you can assure yourself that there is, at most, one relevant photon in the apparatus at any time. Not only will this familiarize you with single-photon detection technology, it will also show you that however two-slit interference is to be explained, it must be explained in terms that can apply to single photons. [And how can a single photon involve itself with two slits?]
4. You will be exploring some theoretical models that attempt, at differing levels of sophistication, to describe your experimental findings. You will thus encounter the distinctions between Fraunhofer and Fresnel diffraction theories in a concrete case and, in addition, learn the difference between a mathematical, and a physical, description of what is going on.

D. Additional goals – the statistics of random-event processes

Two-Slit Interference, One Photon at a Time can also be used to study the statistics of random events. At any arbitrary location in a two-slit interference pattern, both the rate of photon arrival and the time between successive photon arrivals display properties of a random process. You will be able to observe both phenomena and collect enough data to demonstrate that the events are indeed random. You will first make a short set of measurements by hand. Then, using the computer interfacing capabilities of the Pulse Counter/Interval Timer (PCIT), you will be able to gather hundreds of data points to demonstrate random behavior.

1. You will choose a location within a two-slit pattern and take a large set of measurements of events per unit time, or arrival rates. Plotting the number of occurrences for a given set of arrival rates as a function of the arrival rate bin, you will find the Poisson distribution characteristic of random events.
2. Again choosing a location within a two-slit pattern, you will measure a series of waiting-time intervals between successive photon arrivals. You will then plot the number of occurrences of a given set of intervals as a function of an interval time bin. We think you will be surprised by the results.

Chapter 2. Parts Description, Settings and Connections

The goal of this Chapter is to identify the parts of the apparatus and describe the settings and connections needed to power up your instrument so it is ready to use.

The descriptions below assume that the TWS apparatus is fully assembled with the wooden feet and the AMPLIFIER MODULE attached. The apparatus should be in front of you with *its 'source end' to your left and the 'detector end', the* AMPLIFIER MODULE, *to your right.*

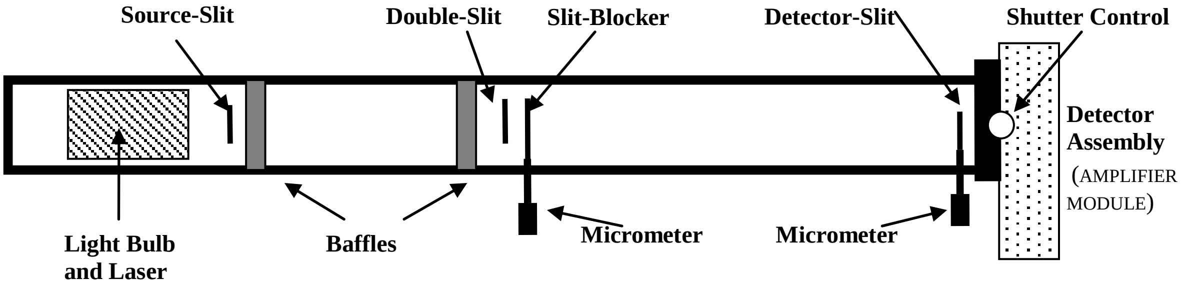
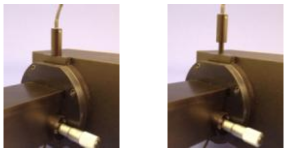


Fig. 1 Schematic of TWS apparatus - not to scale



a. Closed **b. Open**

Fig. 2 Shutter positions

Before Beginning: Make sure that the shutter separating the photomultiplier from the U-channel is securely ***closed*** by pushing down on the (thick part of the) cylindrical projection which emerges from the top of the flange of the AMPLIFIER MODULE. Then, you can remove and set aside the cover of the long U-channel assembly.

A. Components

It is conceptually useful to divide this apparatus into four sections: a light-source assembly, an 'optical bench', a detector assembly in the AMPLIFIER MODULE, and external devices that will indicate either the laser light intensity or the rate of photon arrival events at the point of interest in the interference pattern.

1. The *light sources* are inside the left end of the U-channel and permit either the laser or the bulb to be used. The photo shows the laser in position for use.

   A panel with controls for the light sources and a set of power connections is on the outside left end of the U channel. (See Fig. 6)

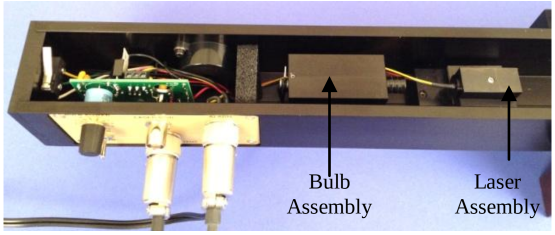


Fig. 3 Source end of open U-channel

2. The *optical bench* lies wholly within the U-channel.
   a. Light passes through a source-slit, encounters a double-slit assembly with slit-blocker, and exits at a detector-slit at the far right end of the U-channel. Baffles located between the source-slit and double-slit prevent stray light from going down the channel.
      - Individual slit widths are all nominally 0.1 mm. By contrast, the opening of the slit-blocker is about 2.0 mm wide.
      - The numbers written on the three sets of double-slits (14, 16, and 18) are in mils (= 0.001") and indicate the center-to-center spacing of the two slits. In metric units these are 0.356, 0.406 and 0.457 mm.

   b. On the side-wall of the apparatus nearest you (near the center of the U-channel's length), there is an external micrometer-adjuster which moves the slit-blocker. Another micrometer, at the far right end of the U-channel, is used to move the detector-slit.

3. The *detector assembly* is the AMPLIFIER MODULE at the far right end of the apparatus, which connects to the U-channel at a circular flange.
   a. Inside that box are **two** detector systems:
      - a solid-state photodiode (for the laser);
      - a vacuum-tube PMT = photomultiplier tube (for photon counting).

   b. Also inside that box are the necessary conditioning electronics:
      - an electronic Current-to-Voltage Converter (for use with the photodiode);
      - a high-voltage biasing supply and a pulse amplifier (for use with the PMT).

Fig. 4 AMPLIFIER MODULE with shutter to photomultiplier closed.

   c. The black rod coming from the back of the detector box controls a shutter that determines which of the detectors is in use.
      - With the rod in the *down* position (Fig. 2a), a photodiode, mounted on the front of the shutter, is in the light path. (Fig. 5)
      - Lifting the rod, as in Fig. 2b, moves the photodiode *out* of the light path and exposes the sensitive portion of the PMT.

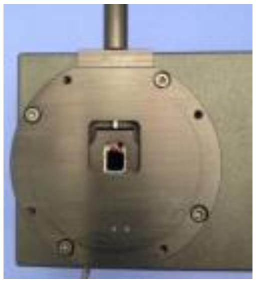


Fig. 5 Photodiode on back of shutter

4. External devices are used to record the output of the photodiode and the PMT
   a. A user-supplied multimeter will register the voltage signals from the photodiode's current-to-voltage converter.

   b. The Pulse Counter/Interval Timer (PCIT) is part of the TWS2-A apparatus and will be used to register the PMT output pulses.

In changing from the LASER to the BULB mode of operation of the apparatus, the source, the detector and the external devices all will need to be changed. But the 'optical bench' is left *un*changed.

B. Settings and connections

1. Safety interlocks (designed to protect the very sensitive PMT from excess light)

   a. The PMT's high-voltage or bias supply can be energized ***only*** when the source switch (at the source end of the apparatus) is set to **BULB** position – the PMT is *de*-energized when either the OFF or the LASER position is selected.
   b. The PMT can *only* be energized when the top cover of the U-channel is closed – there is a microswitch at the extreme left end of the U-channel to enforce this.
   c. If the cover is lifted when the source switch is in the BULB position, the PMT will be de-energized and an alarm buzzer will sound.
   d. If the shutter is opened when the cover is off and the BULB position is selected, the alarm sounds.

2. Initial Settings

   a. At the source end,
      - set the source switch to OFF,
      - set BULB POWER adjuster to minimum.

   b. At the detector end,
      - set the 10-turn HIGH VOLTAGE dial at zero.
      - set the HIGH VOLTAGE toggle switch to OFF

Fig. 6 Light Source Panel on Side of U-Channel

3. Cable connections

   a. A short cable comes from the top of the circular flange on the back of the AMPLIFIER MODULE. Connect its BNC connector to the INPUT of the CURRENT-TO-VOLTAGE CONVERTER section of the AMPLIFIER MODULE (Fig. 4).

   b. From the bottom of that flange there is a long cable with a 2-pin connector. Bring this cable to light source panel (Fig. 6) on the side of the U-channel and plug it into the connection marked ALARM. (This connects a safety interlock in the detector's shutter assembly to the powering of the light sources.)

   c. An external +15-V universal DC power supply (often called a wall transformer or a 'brick-on-a-rope') is part of your apparatus. A wire with a 5-mm diameter circular connector comes from one end. Attach it to the DC INPUT connector on the light source panel.

   d. Use a power cord to bring line power to the power-entry point of the DC power supply.

   e. When all wires have been connected, plug in the line-power end of the power cord. A small green light on the power supply itself will show you that it is energized.

Chapter 3. Alignment

This Chapter assumes the apparatus is assembled and the settings and connections are configured according to the directions in Chapter 2. With the apparatus powered up, you are now ready to align the optical system. The process involves first making sure the light beam from either the laser or the bulb follows a straight and level path down the center of the U-channel, and then installing *four* sets of slits at *three* locations along that path.

A. Deciding how much of this chapter you need to do

1. You will need to go through all of these steps if the apparatus is *new* or has become *completely mis-aligned*.
2. If you only need to *trim up* the alignment, or tweak it after reinstalling the double-slit, you should browse this whole section and then judge where along its route you should begin.
3. If you only want to *check* the alignment, proceed to Chapter 4 to perform the observations described there.
4. If you are *returning* to the use of the laser after having used the bulb-source, you may need only to fine-adjust the source-slit. See Ch. 3 page 4, or Appendix A5.

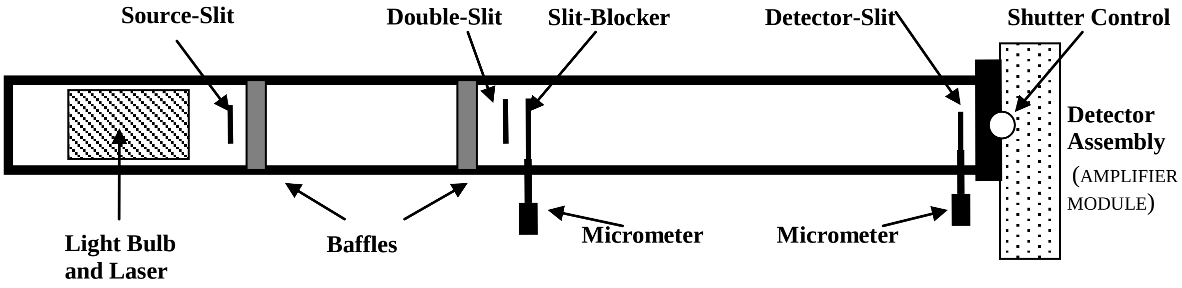


Fig. 1 Schematic of TWS apparatus - not to scale (repeated here for easy reference)

B. Starting from the beginning (The initial alignment starts with no slits in the optical path.)

1. Make sure the shutter is in the down or closed position.
2. In the U-channel, there are two baffles and four blocks each with a circular aperture of < 2 cm diameter. The light path will be directed through their centers of the apertures. (The slits will later be mounted on the blocks)
3. Use the micrometers to *make sure both movable apertures are centered* in the U-channel.
4. For the alignment procedure that follows, you will need one of the T-shaped white alignment cards.

C. Checking the operation and alignment of the *bulb* (Apparatus powered up and shutter closed)

1. Locate the bulb.
    a. Temporarily slide the (magnetically-mounted) laser-source assembly away from you and out of the optical path, to the far inside wall of the U-channel.
    b. Temporarily remove the optical filter from the right-hand (output) end of the bulb-source by grasping its ‘snout’ and turning and pulling.
    c. When you’ve removed this filter, try looking through it at a white-light source. You will see that only a narrow spectral range of lime-green light is coming through.

2. Check that the bulb is working. (You will need a dimly lit room.)
    a. Turn the source-end switch from OFF to BULB and dial the BULB POWER dial from minimum to about half-scale. Use an alignment card, held a few centimeters downstream of the bulb source block, to confirm some yellow-white light is emerging.
    b. The light spreads out broadly so alignment of this source is not very critical.
    c. If no light is emerging, you may need to change the (incandescent) bulb – the procedure is in Appendix A6.


Fig. 2 White Light

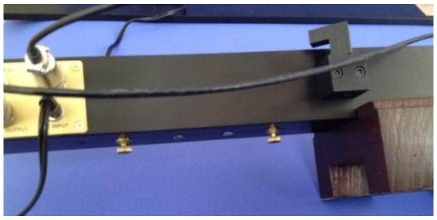


Fig. 3 Thumbscrews on underside of U channel. Left screw adjusts bulb position. Screw on right is for laser.


Fig. 4 Filter


Fig. 5 Green Light

3. Align the white-light beam coming from the bulb.
    a. There is a single thumbscrew available for adjusting the bulb source. Its head is found under the bottom of the U-channel, vertically below the left end (the bulb end) of the bulb-source block. If you loosen this thumbscrew, you'll be able to swing the bulb-source block through an arc.
    b. Put a viewing card into place where the source-slit will be mounted and adjust the bulb block to center the light beam in the optical channel. (This is not a critical adjustment.)
    c. When you've found the best angle, tighten the thumbscrew.
    d. Once you've adjusted the white-light beam, re-install the green-light filter onto the bulb-source. This will markedly decrease the amount of light emerging to your card, but you should still be able to see some light on the card if the room light is dim enough, or if you temporarily dial up the bulb's intensity. If the green spot is not centered, loosen the screw and readjust the block.
    e. Now dial the bulb down to its minimum brightness and set the source switch to OFF.

D. Aligning the laser

1. Setting up the laser and checking the path
    a. Start by sliding the laser toward you across its support block until it fits snugly into place against the near 'shoulder'. This puts the laser approximately on the centerline of the U-channel.
    b. Turn the source switch from OFF to LASER. A beam of red light should emerge. Put an alignment card into the channel to see the beam.
    c. Move the card to follow the laser beam along the length of the U-channel. Notice that as you move away from the laser, the beam widens and becomes defocused.
    d. **The goal of this alignment is to have the laser beam aimed directly down the center of the U-channel all the way to the detector.**
    e. Place the viewing card between the detector-slit block and the shutter.

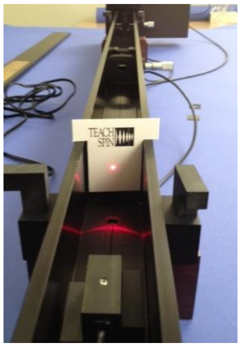


Fig. 6 Viewing Card Near Laser


Fig. 7 Viewing Along U-channel

2. Aligning the path of the laser

   Two adjustments are needed: one to make sure the laser beam travels straight down the center line of the U-channel; the other to adjust the tilt of the beam, its ‘elevation’.

   a. To adjust the path along the center line, you will rotate the block under the laser. Loosen the thumbscrew located to the right on the underside of the U-channel. (See Fig. 3) Move the base under the laser until the beam is best aimed horizontally at the center of the circular aperture at the far right end of the U-channel.
   b. The adjustment for ‘elevation’ is by a 5/64" Allen-head set-screw located at the rear end of the base carrying the laser. (Do not use the set-screw on the laser itself.) Using an Allen wrench, rotate this set-screw, by a fraction of a turn, while watching the laser beam on the viewing card. Find the setting at which the laser beam is best aimed vertically at the circular aperture of the detector-slit assembly.
   c. Once you have the beam centered on the circular aperture and tightened the thumbscrew, the laser is aligned. With the laser now going down the center of the U-channel, you are ready to mount the slits.

Note: You will now *position the slits to conform to the laser beam*. DO NOT re-adjust the laser.

E. Installing the slits

1. *Description of slits and slit placement*

   a. The slits are cut into a non-magnetic sheet which is cemented to a black-oxide steel frame, as shown in Fig. 8. When mounting the slits into the U-Channel, make sure black-oxide surfaces face the rubberized magnetic layer on the slit carrier blocks.
   b. The cover of the box in which the slits are shipped and stored serves as a magnifying glass to examine the slits.
   c. Four of the slits will be installed as follows:
      - nearest the sources – a single slit, referred to as the source-slit
      - near the center of the track, two blocks for slits are set close together. These hold:
        - a double-slit that stays fixed
        - a wide slit (the slit-blocker) that can be moved side-to-side with a micrometer
      - at the detector end – a single slit that can be moved by a micrometer

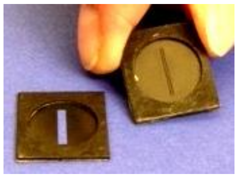
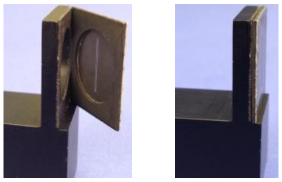


Fig. 8 Wide slit (left) and double-slit (right).

2. *Installing the first slit*, the source-slit, into the optical bench

   a. In the box of slits, find one that has a single narrow slit. Hold it so the slit is oriented vertically, and check to see which side has the black oxide surface.
   b. Mount the single slit to the right-hand, or downstream, side of the circular opening in the first carrier block. Push the slit down so its bottom is flush with the support ledge and the slit itself is approximately centered on the opening. (Fig. 9b)
   c. Place the viewing card between double-slit and slit-blocker holders.
   d. The next goal is to fine-position the ‘source-slit’. Slide the slit from side to side, by fractions of a millimeter, until the central maximum of its single-slit pattern is centered in the circular opening of the two-slit holder. Perfection is not necessary. Your ‘eyeball-sense’ will suffice.



a. Slit ajar b. Slit in place

Fig. 9 Slit support

[Quantitative note: The laser beam emerges with a width of about 1 mm. It is then focused to be less than 1 mm wide when it reaches the source-slit. This slit is only about 0.1 mm wide, so not all the laser light will pass through it. The light that does emerge starts with a width of about 0.1 mm, which (as you will see) is about 150 wavelengths of light wide. For that reason, the light emerging from the slit does *not* continue in one direction. It takes on an angular spread, with divergence of order 1/150th radian. Within a few centimeters downstream of the slit, this divergence makes the emerging light beam spread to a width of over 0.1 mm on a viewing card. By the time the light reaches the double-slit assembly, this divergence creates a bright stripe with a width of a few mm as the central lobe of a one-slit diffraction pattern. This broad central lobe illuminates the double-slits, which are less than 0.5 mm apart.]

3. *Installing the double-slit*
   1. Choose one of the double-slits and **record the number written on the metal film** in which the slits are etched. (This number, 14, 16, or 18 indicates the center-to-center separation of the two slits in thousands of an inch. Example: 14 = 0.014 inches separation.)
   2. Orient the slits vertically with the magnetic material facing the downstream side its support block. (Do *not* mount the double-slit on the micrometer-adjustable slit holder – that's for the slit-blocker.)
   3. Slide the double-slit until the bottom edge is flush with the support ledge.
   4. Position a viewing card a few centimeters downstream of the newly-installed double-slit. Look onto the card and hope to see a pair of vertical red stripes, about 1/3 mm apart. (You may want to view this through a magnifying glass – there's one in the top cover of the little plastic box in which slit-carriers are shipped and stored.) Moving the card a bit farther downstream, you will infer the existence of two thin 'ribbons of light' emerging from the two slits. They are each about 0.1 mm thick, about 1/3 mm apart, and about 1 cm high.
   5. Using this view on a card, make a fine adjustment of the lateral position of the double-slit on its mount. The goal is to center the double-slit on the pre-existing bright lobe of the single-slit diffraction pattern. When you've done so, those two ribbons of light should be equally bright on the card. Again, eyeball equality will suffice.

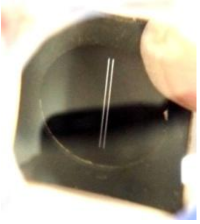


Fig. 10 Double-slit under magnifier

4. *Installing and aligning the slit-blocker*
   1. The slit-blocker is a wide (about 2 mm opening) single slit, which you will mount onto a block whose side-to-side position can be adjusted by the micrometer located near the middle of the U-channel. The two edges of that wide slit will alternately act as 'guillotine blades', which can be positioned to cut off one, or the other, of the two ribbons of light which you've observed.
   2. Mount the slit-blocker onto the *up*stream side of the adjustable support.
   3. Use a viewing card a few cm downstream of the slit-blocker to verify the slit-blocking action. Watch (with a magnifier as needed) the two red ribbons of light as you turn the micrometer that moves the slit-blocker across the optical path. You will use many turns of the micrometer, each of them 'worth' 0.50 mm. You should be able to find two extreme positions:
      - With enough turns of the micrometer inward, the near edge of the slit blocker will guillotine-cut off both ribbons of light;
      - With enough micrometer turns outward, the far edge of the slit-blocker will similarly cut off both ribbons.
      - Over a range of a several micrometer turns in between, *both* ribbons of light will pass through the slit-blocker.
   4. Find the positions at which only one ribbon of light or the other is blocked.
      - Find the position, with the micrometer turned far enough inward, for which the near edge of the slit-blocker will cut off only the *nearer* red ribbon.
      - Turning the micrometer outward, locate the position at which the far edge of the slit-blocker will cut off only the *farther* ribbon of light.

e. Align the slit-blocker.
   - Watch one of the red ribbons appear and disappear as you dial the micrometer back and forth through the required range.
   - If the slit-blocker's edges are accurately vertical (and thus parallel with the pre-existing red ribbons), the light from one slit will go on and off 'all at once'. But if the slit-blocker's slit edges are *not* vertical, you'll see the red ribbon's disappearance start at one end of the stripe and then propagate vertically along the red stripe to completion.
   - If you see this 'partial eclipse' sort of behavior, the correction you need is to rotate the slit-blocker in its own plane. Lift one or the other of the top corners of the slit-blocker, by less than a millimeter and try this test again. You'll have succeeded when you get the desired all-at-once extinction of a red ribbon of light.

5. *Installing the detector-slit*
   a. With the laser still on, with the (single) source-slit and the double-slits in place and the slit-blocker in its *central* position (with two ribbons of light emerging), you are ready to install the detector-slit at the far-right end of the U-channel.
   b. Confirm you are using a single narrow slit. Orient it vertically, and mount it to the downstream, or right-hand side, of the micrometer-adjustable block at the detector end of the optical bench. (See Fig. 1). Again, slide the slit vertically downward until its bottom edge lies squarely on the support ledge.
   c. You will *later* want to make a final adjustment of this slit, rotating it slightly in its own plane. The best method for doing so is to use quantitative fringe detection as in Ch. 5. For now, you do not need this slit to be perfectly aligned, but merely mounted in place.

F. Understanding and reading the TWS micrometer

As part of the alignment process, it is most efficient to *find and record* a set of slit-blocker locations you will need for future experiments. In several of these experiments, you will need to be able to come to these five positions reliably, even when the U-channel is closed.

1. Understanding the micrometer and its relation to the width of an individual slit
   a. The TWS micrometer advances its tip by 0.50 mm for each full clockwise turn of its shaft.
   b. As you will see, cutting off an individual ribbon of light (of thickness about 0.1 mm, set by the width of either of the two slits) occurs not quite 'all at once', but within about 1/5th of a turn. (For our micrometer, this is 1/5 of 0.50 mm, or about 0.10 mm, of motion of the broad slit's guillotine edges.)

2. A short introduction to reading the micrometer

   Each full rotation of the barrel creates 0.50 mm of motion. A reference line along the shaft has two sets of markings. The upper markings on the shaft indicate a translation of 1.00 mm and require two full turns of the barrel. Markings on the lower side of the shaft mark the midpoint or single turn. The series of readings shown below may be helpful. See Appendix A1 for details.

6.00 mm 6.32 mm 6.50 mm 6.96 mm 7.00 mm

Fig. 11 Photographs of micrometer with readings identified

G. Locating and recording micrometer readings for 5 key positions of the slit-blocker

In the diagram below, the five positions of the slit-blocker are schematically depicted, showing how to block one or the other of the light beams emerging from the double-slits. From top to bottom, the slit-blocker moves ‘downward’ on the page relative to the double-slit. This corresponds to dialing the micrometer to larger readings as the shaft is turned counter-clockwise.

It is wise to determine these five readings with the micrometer moving in only one direction to prevent errors caused by ‘backlash’.

1. With the micrometer turned far enough in, both ribbons will be blocked. You can use a reading in this range as a ‘both slits blocked’ setting.
2. If the micrometer is withdrawn just enough, you will unblock only the far ribbon of light. This is the ‘far’ version of the ‘one-slit-only’ setting.
3. Over a rather broad range, both ribbons of light come through the opening. Locations in this area are referred to as ‘both-slits-open’ or as ‘both slits unblocked’.
4. Continuing to turn the micrometer, you will find a location in which only the near ribbon of light is unblocked. This is the ‘near’ version of the ‘one-slit-only’ setting.
5. Finally, with micrometer far enough outward, both ribbons of light are again blocked.

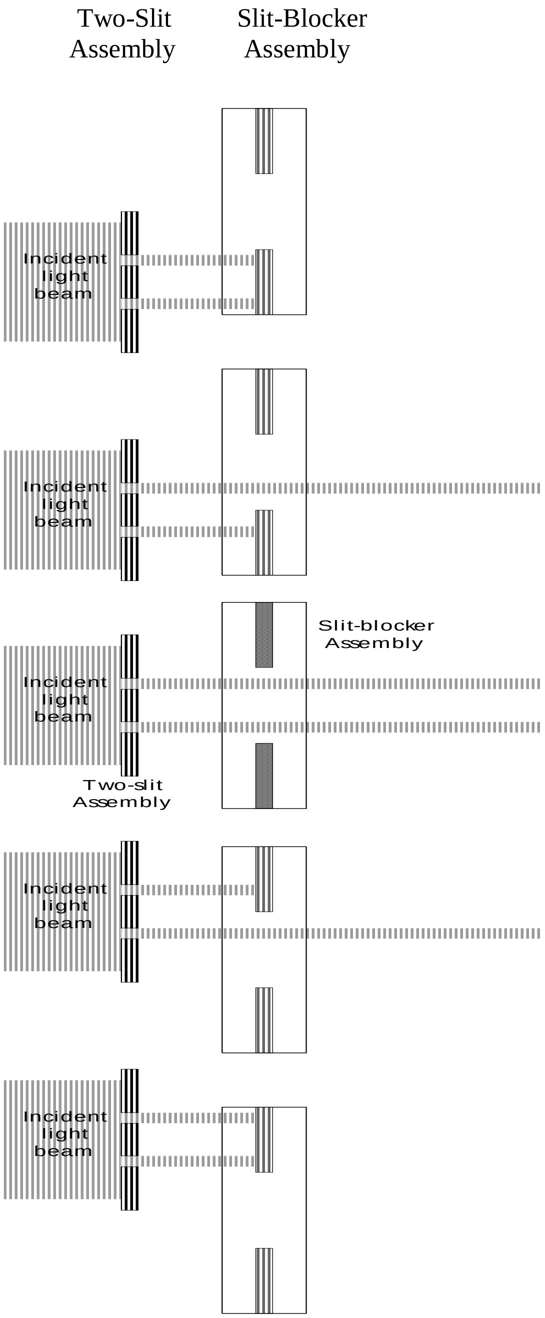


Fig. 12 Critical locations of slit-blocker

Chapter 4. Visual Observations*

With all the slits in place and the system basically aligned, you are ready to make a set of qualitative but crucial observations. The purpose of these observations is to familiarize you with the emergence and appearance of the single-slit and double-slit interference patterns, and with changes in the intensities in these patterns that come from the use of the slit-blocker. In these observations, you will use laser illumination. The only 'independent variables' will be the position along the U-channel at which you place a viewing card, and the setting you choose on the micrometer which adjusts the slit-blocker.

A. Looking at the light pattern from two slits

Turn on the laser and set the slit-blocker so light from *both* of the double-slits passes through.

1. Start with a viewing card placed near the laser to spot the bright beam emerging there.
2. Put the viewing card just downstream of the single slit, the source-slit, and look for a bright spot of light on the card.
3. Now move the card along the U-channel and watch for that spot of light to enlarge, primarily transversely. Watch also for the emergence of a single-slit diffraction pattern, with a clean bright central lobe. Check that this bright central lobe is centered on the double-slit.
4. Next, put the viewing card just downstream of the slit-blocker (which is itself just downstream of the double-slit). Confirm that two equally-bright red ribbons of light emerge. Practice using the slit-blocker's micrometer to cut off either one, or the other, of these two ribbons.
5. Move the card downstream and follow these two ribbons of light. Despite the two-fold collimation of the light involved (first, by the source-slit and then again by one of the double-slits), each ribbon will continue to spread laterally, until the two ribbons begin to overlap in space. Follow that overlap still farther downstream, until you see *not* just an overlapped and broadened ribbon, but instead a pattern of very narrow bright and dark stripes.

   These are the celebrated 'two-slit interference fringes' first studied by Thomas Young. You'll investigate them quantitatively in Chapter 5. For now, cast them onto a viewing card placed just upstream of the final or detector-slit. Be prepared to watch the fringe pattern (through a magnifier, if desired) as you adjust the slit-blocker.

B. Looking carefully at differences between single-slit and double-slit patterns

You are in position to change among the three settings of the slit-blocker, which might be called 'far', 'both', and 'near'.

1. Here are occurrences to note:
   a. Look at the viewing card with*out* magnification and from far enough away so that you don't resolve the individual fringes, but just see the total amount of light reaching the card. Notice that the card is brighter in the 'both' position, and dimmer in the 'near' or 'far' positions, of the slit-blocker. Question: when both slits are open, does it seem as if twice as much light reaches the card compared to when only one slit is open?
   b. Look at the viewing the card close-up or magnified. This time, notice that the 'fringe pattern' of narrow vertical features is *absent* with either one of the single slits open, and present only in the 'both' position of the slit-blocker. How do you interpret this?

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* This chapter could be considered optional, because all of these observations are repeated quantitatively in Chapter 5.

c. With the slit-blocker in the ‘both’ position and viewing close-up, focus on a single location within one bright fringe. Change to a slit-blocker position where only one slit is open. Notice that the light *at your chosen position on the card* gets dimmer. Interpretation: with one, rather than two, slits open, there is less light to reach the card.

d. With slit-blocker in the ‘both slits open’ position, look at the viewing card close-up. Focus on a *dark* fringe – it may help to put a single dark ink-spot on the card and place the card so that the ink spot marks the location of a dark fringe. Move the slit-blocker so only one slit is open. What happens to the brightness on the card *at your chosen location*? Explain.

2. So what does it all ‘mean’? When you make these changes between 1-slit and 2-slit operation, the pattern cast on the card changes. Describe both the changes to the pattern in general and what happens to the brightness at the individual locations you focused on.

   You’ve gone from 2-slit throughput, to *reduced* 1-slit throughput of light. As you saw in 1a, the global illumination of the card goes from brighter to dimmer. But does the same thing happen at every point in the two-slit pattern? Explain.

Chapter 5. Using the Laser-Source and Photodiode to Optimize Slit Alignment and Perform Young's experiment

This Chapter assumes you have read and executed Chapters 1 - 4. The goals of this Chapter are first to use the laser-source and photodiode detector to check and optimize the slit alignment, and then to make quantitative observations of the interference pattern.

The TWS comes with three sets of double slits, differing in their slit spacing. **You must know which set of double-slits, 14, 16, or 18** was installed in your apparatus. ***If you have to remove the double-slit to read the number, go back to Chapter 3 and realign the double slit and slit-blocker before proceeding*.**

A. Setting up

1. Make sure that the shutter protecting the PMT is lowered and then open the U-channel.
2. Using the micrometers, make sure that both movable slit carriers are at the center of the U-channel.
3. Set the source toggle switch to the LASER position and use a T-shaped viewing card to confirm that a beam of red light is emerging from the laser. (The laser power is on the order of 1 mW. While you would *not* want to put your eye into the beam, there is no danger seeing it on the white card.)

B. Checking the light path

1. Check that the laser is snug against the 'shoulder' of the laser support block, and aiming down the centerline of the U-channel.
2. Use the viewing card to follow the laser beam from the laser itself to the first slit – the source-slit.
3. Move the card to just downstream of the source-slit and confirm that a bright visible beam emerges from the slit.

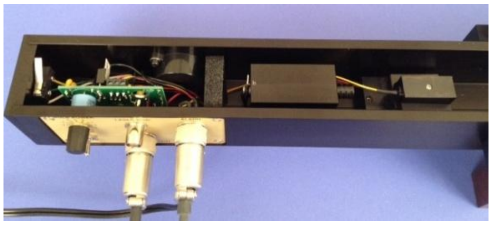


Fig. 1 Source with laser in position for use

4. Move the card along the centerline of the U-channel.
    a. The red beam should spread (due to single-slit diffraction at the source-slit) to give a recognizable single-slit diffraction pattern.
    b. You should see a 'bright central fringe' and nearly symmetrical and less-bright side fringes to both sides. The central fringe will be about 5 mm wide by the time your card is near the middle of the apparatus.

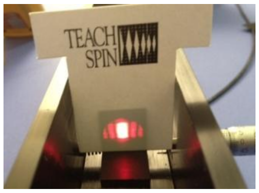


Fig. 2 Single slit pattern

5. Put your card just downstream of the double-slit assembly. Two vertical ribbons of light should be emerging from the two slits. They will be less than 1/2 mm apart, so you will have to look closely. (If the slit-blocker is not centered, one or both of the beams might be blocked. You may have to turn the slit-blocker's micrometer until you can see the double ribbon.)
6. Finally, use the card to follow this 'double ribbon' downstream, until further diffraction causes the two ribbons to overlap. By the time your card reaches the detector end of the U-channel, you should see two-slit interference fringes of < 1 mm spacing.

If, at any point along this progression, you fail to see these phenomena, go back to the alignment procedure of Chapter 3 to correct the problem.

C. Connecting the photodiode and using it to optimize detector-slit alignment

1. Introducing the photodiode detector
    a. The photodiode is *not* a camera and does *not* perform imaging. Instead, it is a ‘bucket detector’ about 1 cm^2 in size, which generates an electrical current proportional to the total light incident on its active area.
    b. To get this detector to produce a 1-dimensional image of the interference pattern, you’ll use the detector-slit to pick out one narrow vertical stripe of the 2-d interference pattern you’ve been seeing on a card and to pass *only* that stripe of light onwards to the photodiode.
    c. As indicated by its name, a CURRENT-TO-VOLTAGE CONVERTER (I-to-V CONVERTER) transforms the photodiode current into a voltage. This voltage is then used as an indication of the amount of light coming through the detector-slit.
    d. As you turn the micrometer, moving the detector-slit across the interference pattern, the amount of light passing onward to the detector ought to vary between a maximum (when the slit is centered on a ‘bright fringe’) and a minimum (when the slit is centered on a ‘dark fringe’).

Fig. 3 AMPLIFIER MODULE with I-to-V converter connected to multimeter

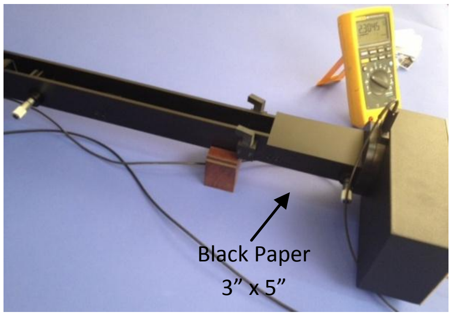


Fig. 4 System ready to take photodiode measurements

2. Connecting the photodiode detector
    a. Make sure that the shutter assembly is fully down by grasping and pushing down on the thick part of the shutter-shaft. This puts the photodiode into position behind the detector slit (see page 2-2).
    b. Connect the BNC jack on the photodiode’s thin coaxial cable to the INPUT of I-to-V CONVERTER, shown schematically in the PHOTODIODE section of the AMPLIFIER MODULE.
    c. Connect a digital multi-meter or other voltmeter, to read the potential difference appearing at the OUTPUT of the I-to-V converter.
    d. To take measurements without closing the U-channel, place a piece of heavy black paper over the detector-slit section of the U-channel as shown in Fig. 4. We used a 3” x 5” strip and it worked well. You may need a longer one if the room is very bright.
3. Locating the 2-slit pattern
    a. For reasons discussed in Appendix A3, you might expect a signal of the order of a few volts at the output of the I-to-V converter.
    b. The peak signal will occur if you have optimally aligned the apparatus, positioned the slit-blocker so light passes through *both* of the double slits, *and* positioned the detector-slit to overlap the *central maximum* of the two-slit interference pattern.
    c. If your peak signal is under half a volt, a re-alignment is likely to give you a larger signal.

4. Finding the central maximum for two-slit operation
    a. Set the slit blocker for two-slits open.
    b. Find a local maximum. Turn the micrometer until you find other local maxima. Recording voltage values, move the detector-slit around until you find one particular local maximum giving a signal bigger (by about 20%) than the local maxima on either side of it. EUREKA – you have located the central maximum!
    c. Use the central maximum to check for background effects.
    Once you have found the 'central maximum', use your viewing card to alternately block and unblock the laser beam back near its source, to find out what portion of your signal is due to the laser. The laser-blocked residual signal will come from both room light and a possible 'zero offset' of the I-to-V converter. A longer black strip, or turning the apparatus to face away from a light source, should help. [For the ultimate in room-light rejection and low-noise operation, see Appendix A2 for how to modulate the laser-source on and off and use lock-in detection of the photodiode signal.]

D. Using central maxima-to-minima contrast to optimize detector-slit alignment

The principle of this alignment is illustrated in Fig. 5. The detector-slit is shown misaligned so that light from both the dark and light areas of the interference pattern reaches the detector at the same time. Rotating the slit until it is parallel to the fringes will substantially improve the contrast.

1. Once you have found the 'central maximum', find the adjacent *minima* to either side of it.
2. The 'iteration' process is to take a set of voltage readings, rotate the detector-slit slightly in its own plane, and re-measure. Continue to tweak the angle of the slit back and forth until you are satisfied with the contrast.

Ideally, the signal at the minima should drop nearly to the 'background' level due to room light and/or zero offsets. By adjusting the detector-slit, you should be able to get the signal at the 'central minima' to be well under one-tenth of what you see at the central maximum.

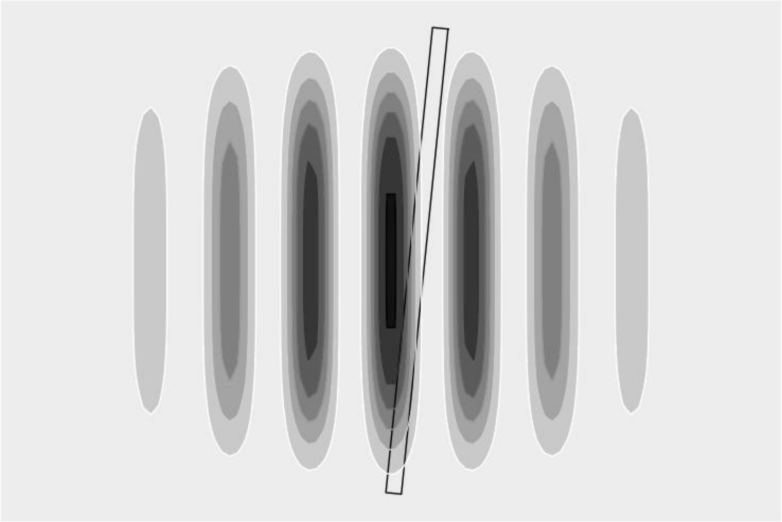


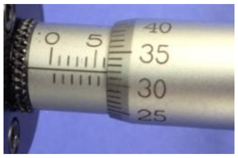
Fig. 5 A schematic face-on view of a fringe pattern and a mis-aligned detector slit. Because the detector slit is not parallel to the fringes, it cannot be located so that it will optimally overlap either a minimum or maximum in the pattern.

There are many ways to approach Young's Double-Slit Experiment. The following series is just one of them. The instructor should feel free to suggest other paths.

E. Preliminary observations of the two-slit and single-slit patterns

1. Introduction
   a. This section assumes you are getting the proper signals from the photodiode's I-to-V converter, as described in the previous section. It will lead you through some initial measurements which will give results that might surprise you.
   b. To perform these experiments, you will need to have located the 'central maximum' and the two 'central minima' of the two-slit pattern.
   c. You will need to be able to set the detector-slit reliably to these locations.
2. **Determine or check** the key locations of the slit-blocker and review their effect on the downstream light in the U-channel. (See Chapter 3 sections F-G & Appendix A1)
   a. Turn the handle of the slit-blocker micrometer clockwise as far as it will go. This will move slit-blocker close to the far side of the U-channel.
   b. Put your viewing card just downstream of the slit-blocker. Because both slits will be blocked, no light will be visible.
   c. Keeping the viewing card in place, slowly rotate the slit-blocker micrometer handle counter-clockwise and note that you see:
      - First, no light at all: both slits blocked
      - Over a narrow range, one ribbon of light: one slit blocked
      - Over a rather wide range, two ribbons of light: neither slit blocked
      - One ribbon of light again: the *other* slit blocked
      - Finally, no light at all: both slits blocked again
   d. When you have observed these phenomena, and understood them in terms of the guillotine action of the slit-blocker edges, **record the five settings of the slit-blocker's micrometer which will reliably put you into the five states listed above**.
3. **Put the cover on the U-channel**
   a. Be sure the cover is fully lowered into place, first at the detector end (where it will slot into the round flange), and then at the source end.
   b. Engage the four latches that hold the cover shut.

6.00 mm



6.32 mm

6.50 mm

6.96 mm
Note: this is 6.5 + .46

7.00 mm

Fig 6. A reminder of how to read the micrometer

4. Observations with detector-slit at central maximum
   a. Set the slit-blocker so both slits are open.
   b. Set the detector-slit at the central maximum. This voltage is proportional to the intensity of the light coming through the detector-slit.
   c. Measure this voltage in turn for the five settings of the slit-blocker. Two of these readings will be measurements of 'zero offsets'; two more will be readings of light intensity when only one slit is open. The central one of the five will be a reading of light intensity when both slits are open.

- d. Use the zero-offset readings to ‘correct’ the readings for the single and double slit voltages.
    - Observation: Compare the values and see if the voltage with the slit-blocker in the central region (two-slit intensity) is the *sum* of the readings for the two single slit voltages (one-slit intensities).
    - Explanation: The wave-based explanation of this is pretty simple, since it is *wave amplitudes* that are expected to add up. So if one-slit-illumination gives a wave amplitude of 1 (in some set of units), and if the other-slit-illumination also gives a wave amplitude of 1 (in the same units), then under conditions of constructive interference, you expect a wave amplitude of 2 under conditions of both-slit-illumination. And doubling the wave amplitude will give *four* times the wave intensity.

5. Observations with the detector-slit at one of the **‘**central **minima’**
    - a. Set the slit-blocker so both slits are open.
    - b. Set (and *leave*) the detector-slit so that you are at one of the ‘central minima’.
    - c. Measure the voltage in turn for the five settings of the slit-blocker.
    - d. Correct the three interesting readings for zero-offsets.
        - Observation: Compare the two-slit open intensity to the sum of the individual slit readings.
        - Explanation: The wave-based explanation of this phenomenon is also pretty simple, since it is wave amplitudes that are expected to add up. So if one-slit-illumination gives a wave amplitude of 1 (in some units), and if the other-slit-illumination also gives a wave amplitude of 1 (in the same units), then under conditions of destructive interference, you expect a wave amplitude near 0 under conditions of both-slit-illumination. And no wave amplitude means *no* wave intensity either.

NOTE: You will not, especially on a first try, achieve results quite as dramatic as ‘$1 + 1 \approx 4$’ or ‘$1 + 1 \approx 0$’, since reaching either of these limits requires almost perfect alignment. The quadruple-or-nothing behavior assumes you have equal illumination of both slits and that the light from the one slit is fully coherent with the light from the other. Your first indication of this dramatic result will be simply be showing that ‘$1 + 1 > 2$’ at the two-slit central maximum. It will be even more impressive when you see that, at the central minima, not only do you find ‘$1 + 1 < 2$’, but also that ‘$1 + 1 < 1$’! In other words, you will have shown that the joint effect of having both slits open is not only *less than the sum* of the two one-slit signals, it is also *less than the signal from either* single slit alone.

F. Measurements to record before doing the Young's Experiment

1. Go back to the two-slits-open condition. Using your micrometer, find and record the detector-slit locations of the central maximum and two or three local maxima on either side.
2. Find and record the detector-slit locations needed to attain the 4 or 6 local minima that occur between these maxima.
3. See if you can establish that the maxima are uniformly spaced, and make an estimate for the spacing between adjacent maxima.

G. An approximate calculation of the wavelength of the light you are using

1. **Question 1**: Taking the location of the central maximum as defining a zero of angle, by what angle are you off-axis when you are at the next-to-central maximum? (What new *length* do you need to measure to establish this angle?)
2. **Question 2**: Find the textbook derivation of the result written as $n \lambda = d \sin \theta_n$ and explain why $n = 1$ is appropriate for the next-to-central maximum.
3. Use your computed value of θ_1 to compute the ratio λ / d.
4. The double-slit assembly that you have installed in the apparatus is marked with the hand-written digits 14, 16, or 18. These correspond to values of *d*, the center-to-center separation of the double slits, of 14, 16, or 18 mils = 0.014", 0.016", or 0.018" = 0.356 mm, 0.406 mm, or 0.457 mm.
5. Use your results to compute λ, first in mm-units; then convert to μm and/or nm units.
6. Compare the wavelength you computed with the color you see, and with what you've been told about optical wavelengths.

This will not be a final value of the measured wavelength, so you need not yet perform a full uncertainty analysis. The real reason for doing this calculation at this point is a plausibility check on your data and calculations in the next section.

H. Measuring light intensity as a function of location as the detector-slit is moved across the photodiode

Now that you have been introduced to some of the surprises that can emerge from this apparatus, it is time for you to examine the entire single and double slit diffraction patterns.

1. The students should develop a strategy for efficient, yet precise, collection and analysis of data.
2. They should also consider how best to present this information graphically.

It is crucial that you plot your data set either as you are taking it, or right after you've completed an individual scan, to see if it makes sense as a graph. If you worry about repeatability, you should consider the issue of 'backlash' of a micrometer. How would you deal with this?

I. Data modeling and data reduction

Now that you have taken data across a wide section of a two-slit or one-slit pattern, you might wish to do a more complete theoretical model than merely to locate the maxima of the interference fringes. On what curve(s) should your data points lie? What is the influence of the slit width *a* (and not just the slit separation *d*) on the shape of the data? What is the 'best-fit' value of the ratio λ / d? How well do the assumptions of the simplest textbook models correspond to your actual conditions, and can you do better? These matters are all addressed in Chapter 8 of this Manual.

Chapter 6. Setting Up for Single Photon Counting Using the PCIT

A. Introduction to the Pulse Counter/Interval Timer (PCIT)

The goal of this section is to introduce the PCIT, identify its parts, and show you how to connect it properly to both your Two-Slit apparatus and an oscilloscope.

1. Modes of operation

The PCIT has two modes of operation: PULSE COUNTER and INTERVAL TIMER. Within each mode, either MANUAL or AUTO operation can be selected. In MANUAL operation, a measurement is made every time the AUTO/MANUAL toggle is depressed. For AUTO operation, the REP RATE GATE setting chosen determines the time between successive measurements.

a. Pulse Counter

In this mode, the PCIT counts the number of electrical pulses that satisfy the DISCRIMINATOR THRESHOLD criterion during a 0.1, 1.0 or 10 second time period selected by the experimenter.

b. Interval Timer

In this mode, the timer records the time between the arrivals of two sequential pulses satisfying the discriminator criterion. Again, the experimenter can choose either manual or auto operation.

c. Computer Recording

In either mode of operation, the data can be sent to and recorded by a computer. For statistical investigations, where a large amount of data is needed, this capability is particularly important.

2. An overview of the components

The diagrams below show both the front and back panels of the instrument. The parts of the front panel are listed left to right on the upper, then lower, rows.

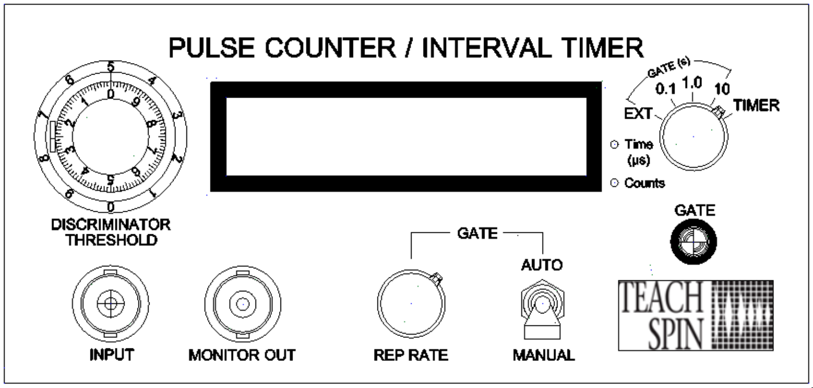


Figure 1. Front Panel of PCIT

Fig. 1 Front Panel

Upper row

1. **Discriminator Threshold Adjust**
2. **LED Display**
3. **Function Indicators**
4. **Function Select Switch**

Lower Row

5. **Pulse Input BNC**
6. **Monitor Output BNC**
7. **Gate Repetition Rate Control**
8. **Auto/Manual Switch**
9. **Gate LED**

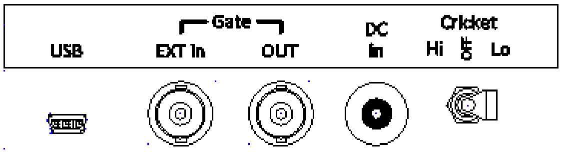


Figure 2. Back Panel of PCIT

Fig. 2 Back Panel

10. **USB connection for computer**
11. **Gate access for external control**
    - **a. Ext In**
    - **b. OUT**
12. **DC power input**
13. **Cricket settings for Hi/Off/Lo**

The individual components and their uses are described below. The number in parenthesis indicates the location on the panel.

a. Function Select Switch (4) and Function Indicators for Display (3)

The rotary selector switch (4) controls the mode of operation of the PCIT. The Function Indicator LEDs (3) indicate whether that mode is Pulse Counter (Counts) or Interval Timer (Time (μs)).

TIMER: If set on TIMER, the PCIT measures the time in microseconds between successive pulses that meet the discriminator criterion.

GATE (S): For all selections within GATE (S), the PCIT is in its counter mode, and the user can choose among several options for the time period during which pulse arrivals will be counted. Three internally generated gate intervals are available: 0.1 s, 1.0 s and 10 s.

EXT: When EXT is selected, the timing is controlled by a user-supplied external gate which can be connected via a rear panel BNC connector at Gate, EXT In. (11a)

b. Gate OUT – on rear panel (11b)

Located on the rear panel, a BNC connector labeled Gate OUT carries an exact copy of the measurement gate used during pulse counting operations. This signal can be used to trigger other external apparatus or processes.

c. REP RATE - Gate Repetition Rate Control (7**)**

Quite often in a teaching environment, students will be required to collect a number of data points on which they will perform some sort of statistical analysis.

The Gate Repetition Rate control is actually a 'gate delay' that allows students to adjust the amount of time between successive readings when using the PCIT in the counter AUTO mode. It is particularly useful with short gate times to make sure there is time to *manually record* a result before a new measurement cycle begins. The time delay is adjustable between 0.5 and 5 seconds. Note: This feature is not available when the PCIT is used in the counter MANUAL mode, or as a TIMER.

d. AUTO/MANUAL Switch (8)

When this switch is set to AUTO, all intervals and repetition times are internally controlled.

For MANUAL operation, the toggle starts in a 'neutral' position and is depressed briefly to initiate a measurement. The PCIT then counts for whichever gate (s) interval has been selected and sends the result to the Display.

e. PULSE INPUT BNC (5)

Pulses generated by the PMT of the TeachSpin Two-Slit or other appropriate apparatus enter the system though this BNC.

f. MONITOR OUT BNC (6)

This is an output that produces one positive pulse of 0.5 V amplitude for each input pulse that satisfies the discriminator condition.

g. DISCRIMINATOR THRESHOLD (1)

The discriminator sets a minimum voltage above ground required for an incoming pulse signal to be counted. The DISCRIMINATOR THRESHOLD rotary dial controls a 50-ohm terminated, high-speed discriminator and allows the user to adjust the threshold level of the pulse stream. Typically, the user monitors the INPUT pulse on Channel 1 of an oscilloscope, connects the MONITOR OUT of the PCIT to Channel 2 and triggers on Channel 2. The threshold control can then be adjusted until the desired pulse level is being captured.

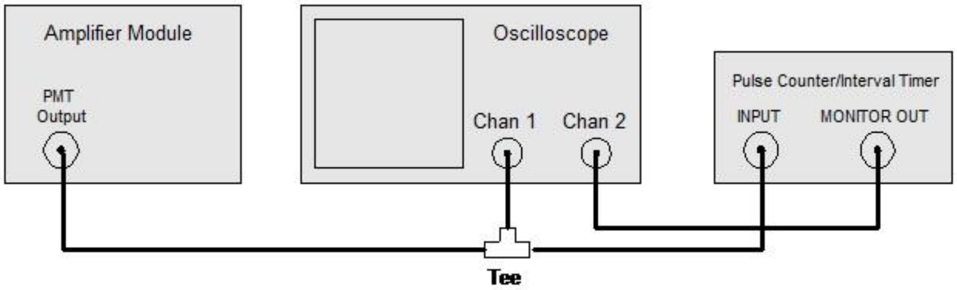


Fig. 3 Schematic for connecting Amplifier Module of the TeachSpin TWS to PCIT and oscilloscope

NOTE: The Counter/Timer INPUT BNC is internally terminated with 50 ohms. It is important that the Counter/Timer be the last instrument in the connection chain. For instance, as described above, the output of the Two-Slit instrument is connected via a BNC cable to one channel of the 'scope through a T-connector and the counter connected to the T with a second BNC cable. Avoid placing the counter in the middle of a cable run, or diminished performance will result.

h. LED Display, Function Indicators (2, 3)

A 6-digit LED panel displays the data. The two small LEDs to the right of the display panel indicate whether the number shown is an event Count or a Time (μs) interval. If the upper light is lit, the number displayed is a count of the number of events that occurred during the selected gate time. If the lower light is on, the display indicates the total number of microseconds that have elapsed between two consecutively-occurring pulses, also referred to as an event pair. In either case, the number is an integer.

An overflow condition in either the count or interval function is entirely possible and will be indicated by a display of '------', and occurs when the displayed value exceeds 999,999. Causes for this could be that the discriminator level is set too low and the instrument is triggering on noise or AC ripple rather than pulses generated by photons, or that too long a timing gate is being used for the desired measurement.

An overflow condition may occur in either the MANUAL or AUTO modes. In MANUAL mode, the overflow indication will remain in the display until a new reading is selected, the mode is changed to AUTO, or the function is changed.

In AUTO mode, the display only operates in the Counts mode. In TIMER mode the display will show the letters USB, as a reminder that this mode requires computer interfacing. An overflow indication will remain in the display until the delay timeout occurs and a new reading is initiated.

i. GATE LED (9)

When this light is on, the PCIT is counting pulses.

j. Cricket (Rear Panel - 13)

Cricket is our name for the feature which allows students to hear a cricket-like 'chirp' every time a pulse has met the DISCRIMINATOR THRESHOLD criterion. The control for the Cricket is a small toggle switch on the rear panel of the instrument. The center position is off. Setting the switch to either side will both turn it on and select one of two volume levels. The high level can be used in a lecture hall. The low level setting provides a soft background audio representation of the input pulse stream.

The following sections prepare you to use the PCIT in a mode in which it detects and counts photons *one event at a time*. We assume that you have aligned the apparatus (Chapter 3), and that you have completed Young's experiment in laser-source mode (Chapters 4 and 5). These sections include the procedures for changing over from laser to light-bulb operation, and teach you how to understand and optimize the use of the PMT (photomultiplier tube) and PCIT (Pulse Counter/Interval Timer) for single-photon detection.

B. Converting to light bulb as source operation

1. Before beginning
   a. With the cover closed, be sure the shutter covering the PMT is down. On the AMPLIFIER MODULE, confirm that the HIGH VOLTAGE toggle is in the OFF position and the 10-turn dial is turned all the way counter-clockwise and is reading 0.00. You can then remove the cover from the U-channel.
   b. In case you have not done so already, or are coming back after someone else has used the apparatus, you will need to determine or verify a series of important settings needed for the slit-blocker's micrometer.

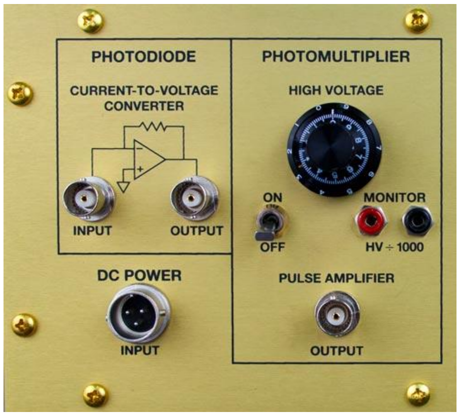


Fig. 4 Controls on AMPLIFIER MODULE

   - Set the source toggle to LASER (Fig. 5).
   - With the top cover off and a black card in place to eliminate much of the room light, review and record the micrometer settings you need to get 'far-slit', 'both-slit', and 'near-slit' operation as described in ***Chapter 3 Section F & G***.
   - Remember that in bulb-source operation, you will need to be able to come back to each of these settings, with*out* being able (as you are now) to 'open the box' for confirmation.

   c. With the slit-blocker in the both-slits open position, make sure the detector-slit is at the central maximum.
   - Check by eye to see if the detector slit is centered in the two-slit pattern.
   - Connect your multimeter and record the voltage reading at this location.
   - Use the micrometer to move the detector-slit until you find the local maximum and record both the voltage and micrometer readings.
   - Again using the micrometer, find the local maxima on either side to verify that you have indeed found the location of the central maximum.

When changing from laser-source to bulb-source operation, note that you will **make no changes to the slit arrangement in the U-channel**. Everything, from the source-slit to the detector-slit (inclusive) stays the same, with no change in alignment or in use. All that you need to change is the source from laser to bulb, and the detector from photodiode to photomultiplier.

2. Changing the source from laser to bulb
   a. Set the source switch toggle to OFF and turn the BULB POWER knob to half-scale. (Fig. 5)
   b. For the safety of the PMT, confirm that the high-voltage 10-turn dial on the detector end of the apparatus is set to zero and that the high-voltage switch there is set to OFF. Also, to be sure the PMT is closed off from any possible light, check that the shutter is in the *down* position.

Fig. 5 Light Source Panel on Side of U-Channel

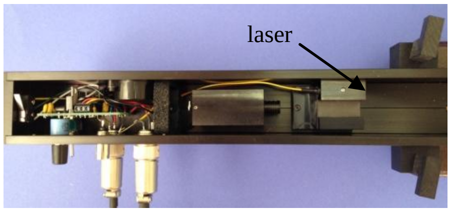


Fig 6. Light source configured for bulb

c. At the source end of the apparatus, locate the block which encloses the laser and slide it, on its magnetic coupling, to the far inside wall of the U-channel as shown in Fig. 6. This opens the optical path for light to pass from the bulb source to the source-slit.

d. Turn the source switch from OFF to BULB, which should turn on the incandescent bulb-source.

   To confirm the bulb is working, you'll need a dimly-lit room and a viewing card held just a few centimeters downstream from the bulb. You should see a dim and somewhat diffuse green spot on the paper. You should not expect to be able to 'follow the beam' very far downstream using a card, although in a dim enough room, with the BULB POWER set ***temporarily*** to high on its scale, you might be able to follow the green light to, and just past, the source-slit.

e. Once you've confirmed the bulb is working, you *must close* the cover of the U-channel.

   - Be sure the cover is fully lowered into place. **First, slide the cover into the slot in the round flange at the detector end.** Then, lower it over the source end.
   - Engage the four latches that hold the cover shut. This closure of the box is necessary to make the interior space dark enough for the PMT's safety. An interlock switch should prevent PMT operation if the cover is ajar.

3. Changing the detector

   a. You can leave the photodiode cable-connection to the input of the I-to-V converter in place. However, you will not be using that signal channel.

   b. When you are ready to use the PMT, you will grasp and lift the shutter by pulling on the thick part of the shaft, *not on the cable*! This operation takes the photodiode out of the light path. The light passing through the detector-slit will now reach the sensitive area of the PMT.

4. Interlude – Laser vs. bulb as source. This section illustrates what 'bright' and 'dim' mean in the present context, and why it's necessary to change the detector as well as the source in this change-over. More details can be found in Appendix A3.

   a. We'll compute an approximate rate of photon arrivals corresponding to the bright-light signals you've been getting in laser-as-source operation.

      - At the peak of the central maximum of the two-slit interference pattern, good alignment might give a signal of order 3 Volts (against a laser-off background of 0.01 V or less).
      - For 3 Volts to emerge from the I-to-V converter, the current entering it had to be 3 V/22 MΩ or about 0.14 μA.
      - Now for red light, the responsivity of your photodiode is about 0.5 A/W, or 0.5 μA/μW. Therefore, about 0.28 μW of red light was coming through the detector-slit and reaching the photodiode.
      - That red light arrives as photons of the 670-nm light field, so each such photon delivers an energy of $h\,f = h\,c\,/\,\lambda = 3 \times 10^{-19}$ J.
      - Since energy is arriving at rate 0.28×10^{-6} J per second, you can infer the photon arrival rate was $(0.28 \times 10^{-6}$ J/s$)\,/\,(3. \times 10^{-19}$ J/photon$) = 0.09 \times 10^{13}$ photons/s or about 9×10^{11}, say 10^{12} photons per second.

   b. Since you are about to perform two-slit interference experiments with a photon event rate of order 10^3 photons per second instead, you can immediately see that typical 'dim light' is fully **10^9-fold dimmer**, one one-billionth of the intensity, of the bright light you've been using.

   c. Put another way, if the laser source gave you 3-V signals at the interference pattern's central maximum, the bulb-source, with the same photodiode detector, would give you signals of order 3 *nano*Volts. These signals would be lost in the electronic baseline noise of the I-to-V converter, and in any case the signals would certainly not be detectable as discrete individual events.

C. What a PMT does and how it works

1. Description:

   A photomultiplier tube (PMT) is a very artfully constructed vacuum tube, which uses the photoelectric effect at a photocathode to produce a single free electron in response to a photon of light, and which also amplifies this one-electron 'charge pulse' to macroscopic levels. It is a remarkable tool for detecting a single-quantum event.

2. The 'Quantum Mystery'

   There is one mystery along the way, related to the famous 'measurement problem' of quantum mechanics. Any quantum field theorist will tell you that the quantum state of light in any given spatial mode is a superposition, which could be written as

   $$\left|\psi\right\rangle = \alpha_0\left|\varphi_0\right\rangle + \alpha_1\left|\varphi_1\right\rangle + \alpha_2\left|\varphi_2\right\rangle + \ldots \quad ,$$

   where the ket-state $|\varphi_i>$ represents a 'number eigenstate' having exactly *i* photons in the mode. Here the complex numbers α_i give probability amplitudes, so that $|\alpha_1|^2$ gives the probability of detecting exactly one photon in a measurement of the state $|\psi>$. So the theorists' light beam going into the PMT is a *superposition* of possibilities, or potentialities, of getting no photons, getting one photon, etc. But what comes out of a PMT is *not a superposition* of no pulse, one pulse, etc.; instead it is *either* no pulse *or* one pulse. Somewhere along the way, the quantum superposition has turned into a classical event, and a combination of multiple potentialities has turned into the actualization of only *one* of them.

3. Approximate calculations of the TWS photomultiplier output

   Even at the empirical level, there are remarkable features about a PMT such as the Hamamatsu R212 used in the TeachSpin TWS. The manufacturer's data shows that the response of the photocathode to light, as function of wavelength, drops precipitously for wavelengths above $\lambda_{cr} \approx 700$ nm. We may infer that light of longer wavelength (i.e. of lower frequency) has photon energy too small to eject an electron from the photocathode. That in turn allows us to compute the work function of the photocathode.

   $$\varphi = h\, f_{cr} = h\, c / \lambda_{cr} = 2.8 \text{ x } 10^{-19} \text{ J or } 1.8 \text{ eV}.$$

   In the TeachSpin TWS apparatus, such a photocathode is used to detect green-light photons with a wave length of $\lambda \approx 550$ nm, whose photon energy is 2.3 eV. The picture of a successful photo-detection event, therefore, is that a single electron emerges from the photocathode into vacuum, with a maximum kinetic energy in the range of only (2.3 - 1.8) = 0.5 eV. Once that electron emerges, the charge-amplifying mechanism of the PMT takes over.

   Interestingly, despite the name, it is not photons, but *electrons*, that get multiplied in the photomultiplier tube. If there is a high-voltage 'bias' applied to the tube, then this solitary photoelectron finds itself in an electric field that has been set up in the space between the photocathode and the first 'dynode'. The electric field then accelerates the electron toward that dynode.

   Depending on the bias level used, the electron might traverse a potential difference of order 50 V, so it will arrive at the first dynode with kinetic energy not of 0.5 eV, but of 50.5 eV. That is a value much larger than the work function of any conductor, and the dynode is made of a material optimized for 'secondary electron ejection'. This means that the impact of the 50-eV primary electron will eject *several* 2nd-generation electrons from the dynode. Each of these will in turn be accelerated toward a second dynode, where each will produce, by the same mechanism, several 3rd-generation electrons.

We can actually make a rough calculation of the current produced by our PMT and the pulses we will be detecting. In the R212 tube, there are $N = 9$ stages of the 'electron multiplication' events just described. If r gives the electron-multiplication factor at one dynode, the net result after the whole chain of dynodes is a charge pulse of $q \approx (-1\ e)\ (r)^N$ arriving at the final electrode of the PMT, the anode.

For $r \approx 4$ and $N = 9$, this means that the event initiated by a single photon, liberating just *one* electron from the photocathode, has been turned into a charge pulse of $q \approx -e\cdot(3 \text{ x } 10^5)$. This pulse thus carries a charge of $- 4 \text{ x } 10^{-14}$ C.

This still sounds like a small charge, but since all the *N*th-generation electrons arrive in a time interval of just a few ns, the instantaneous current during the pulse is of size about $(4 \text{ x } 10^{-14}$ C) / (few x 10^{-9} s) $\approx 2 \text{ x } 10^{-5}$ A or about 20 μA.

An 'instantaneous' current of 20 μA flowing through a 50-Ω resistor, would produce a pulse with an amplitude of a full millivolt. That pulse is the result of the impact of just one photon on the photocathode. We have produced a macroscopic consequence of a microscopic 'quantum event'.

Note, however, that not every photon that strikes the photocathode of a PMT produces an emerging photoelectron. In fact, the 'quantum efficiency' of the R212 PMT for the green photons we are using is only 5 or 6%.

4. Amplification of the PMT pulse

Within the detector-assembly, the AMPLIFIER MODULE, there is one stage of linear amplification of the photon-induced, PMT-multiplied charge pulse. The (negative) charge pulse arriving at the PMT's anode is sent through a 100-Ω resistor, and the resulting voltage pulse is amplified by gain (-20) to produce a positive voltage pulse.

An example: For the choice of high-voltage bias which gives an amplification of $3 \text{ x } 10^5$ inside the PMT, the charge pulse at the anode is $(-1.6 \text{ x } 10^{-19}$ C)$\cdot$ $(3 \text{ x } 10^5) \approx 5 \text{ x } 10^{-14}$ C. The duration of that pulse is about 2 ns, giving a current of about $-3 \text{ x } 10^{-5}$ A. The current is then passed through a 100-Ω resistor to produce a voltage pulse of $-3 \text{ x } 10^{-3}$ V or -3 mV. Finally, the active amplification by factor (-20) produces a +60-mV pulse, which appears at the BNC output labeled PULSE AMPLIFIER OUTPUT.

Note that no 'discrimination' has yet been applied, and that all the electronics to this point have been linear and analog. In the TWS2-A design, the analog pulse, now amplified, but still rather small in amplitude, is sent by coaxial cable to the PCIT to be processed.

D. Connecting the PMT to the PCIT and observing pulses

The two main electronic adjustments necessary for photon counting are the HIGH VOLTAGE setting for the PMT on the TWS2-A AMPLIFIER MODULE and the DISCRIMINATOR THRESHOLD setting of the PCIT.

In the laser-source mode, the detector of light was a photodiode mounted on the PMT shutter and located just behind the detector-slit. Lifting the shutter removes photodiode from the light path and exposes the PMT (photomultiplier tube). The PMT's photocathode is where (some) photons produce single photoelectrons. As discussed earlier, single electrons are multiplied inside the PMT to produce charge 'pulses' that are then amplified and converted to voltage pulses that emerge at the PULSE AMPLIFIER OUTPUT of the AMPLIFIER MODULE. These still-low-level voltage pulses are conveyed by a BNC cable to the PCIT INPUT connector. There, internal electronics 'test' each pulse against a 'discriminator level' to see if it meets a voltage-height criterion.

1. Parts needed
   a. Digital oscilloscope
   b. Digital Multimeter (DMM)
   c. Several BNC cables
   d. One BNC T or F connector
   e. TeachSpin PCIT

2. Initial settings of micrometers, U-channel, light source, AMPLIFIER MODULE, and PCIT
   a. Micrometer settings:

      Make sure neither of the double slits is blocked by the slit-blocker, and that the detector-slit is at the previously-established location of the central maximum of the interference pattern.

   b. U-Channel:

      Confirm that the laser module is out of the optical path and **close the U-channel cover.**

   c. Light source settings: Light source settings:

      - **Set the light source toggle to BULB.** (See Fig. 5).
        NOTE: The PMT is powered ONLY with the source switch in the BULB position.
      - Set the *BULB POWER* knob about mid-scale.

   d. AMPLIFIER MODULE:

      - Keep the shutter in the PHOTON COUNTING MODULE in the closed, or 'down' position.
      - Connect your digital voltmeter leads to MONITOR in the PHOTOMULTIPLIER section of the AMPLIFIER MODULE. Set the DMM so it can read voltages around 1 V. (Remember your voltmeter will read 1/1000 of the voltage applied to the PMT.)

   e. PCIT: Set the GATE switch in horizontal (neutral) position so that no counts will register. (You will not need this function until later.)

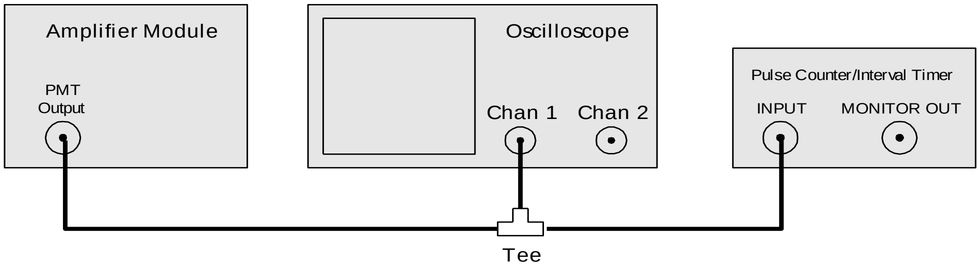


Fig. 7 Schematic for connecting the TWS, oscilloscope, and PCIT

3. Connect the PHOTOMULTIPLIER PULSE AMPLIFIER OUTPUT to the oscilloscope and the PCIT as shown in Fig.7. The voltage pulse originating in the TWS2-A will be terminated in the 50-Ω input impedance of the PCIT, but the 'scope will be able to view that pulse 'in flight' as it passes by.

4. Oscilloscope settings – Channel 1
   a. Trigger Settings:
      Type: Edge Slope: Rising Coupling: DC
      Source: Ch 1 Mode: Automatic Trigger Level: 10 mV
   b. Sensitivity
      Horizontal: 50ns/div Vertical Ch 1: 10 mV/div
   c. In Display, set the Persistence for 1second.

   The ‘scope will display the pulse amplifier’s output voltage noise, which ought to show fluctuations of just a few mV. This is the level against which you hope to see positive-going, photon-caused, pulses with heights of order 100 mV.

5. Looking for pulses
   a. Lift the PMT shutter. Light passing through the detector-slit will now fall onto the PMT’s photocathode. If the cover is not firmly closed, an alarm will sound. If it does, immediately close the shutter and check the cover.

      Although baseline noise may be visible, you should not yet be seeing any consistent pulses.
   b. Energize the PMT
      - Turn the PHOTOMULTIPLIER switch to ON
      - Turn the 10-turn high-voltage dial clockwise until the DMM is reading 0.2 volt (200 V bias).
      - The electron-multiplying gain of the PMT is too low at this bias setting for you to expect any pulses, but you should check to see that the baseline noise level on your ‘scope is still only a few mV.
   c. Increase the PMT high-voltage bias level slowly.
      - Watch to see when the ‘scope starts to trigger. This will probably be around 600 V.
      - Notice the characteristic width in time of the pulses (set largely by the bandwidth of the pulse-amplifier circuit)
      - Notice that the pulses from the PMT now stand above the noise baseline.
      - Continue to 850 Volts. *As the voltage increases, the pulses get higher. Why?*

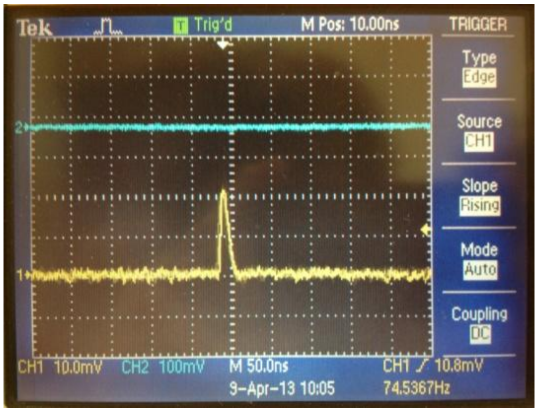

Tek Trig'd M Pos: 10.00ns
TRIGGER
Type Edge
Source CH1
Slope Rising
Mode Auto
Coupling DC
CH1 10.0mV CH2 100mV M 50.0ns CH1 ∕ 10.8mV
9-Apr-13 10:05 74.5367Hz

Fig. 8 Oscilloscope Photograph

6. Check to see how the pulses are related to the light coming through the detector-slit
   a. Set the PMT high voltage to about 700 volts (or 0.7 volts on your multimeter).
   b. Compare the ‘scope signals with shutter open and closed and convince yourself that you are observing much more frequent pulses with the shutter open. This is only a crude demonstration that you are observing photons coming through to the detector.
   c. Note that you are also observing pulses when the shutter is closed. These are so called ‘dark counts’ that occur in all photomultiplier detectors. Once can consider them a form of ‘noise’ since they appear even when the photomultiplier is completely shielded from visible light.

An oscilloscope is an ideal way to see pulse height and shape. It is *not* a good way to count the rate of arrival of pulses. That’s the role of the PCIT. You will now set a *criterion* of what should be counted as a pulse. In the PCIT, the incoming pulse is compared to a voltage-height requirement, set by its 10-turn dial labeled DISCRIMINATOR THRESHOLD.

E. Exploring the effect of the PCIT DISCRIMINATOR

Photomultipliers have significant variations in both their gain and their dark count. These parameters, of course, also depend strongly on the bias voltage applied. What we describe below represents signals we observed for a 'typical' PMT used in this equipment. The signals you observe may vary considerably from these. That will not prevent you from detecting single photons, but the bias voltage and discriminator levels you will end up using may vary significantly.

1. Use another BNC cable to bring the MONITOR output of the PCIT to the Channel 2 input. (See Fig 3.)
2. Set the PMT voltage on the AMPLIFIER MODULE to 900 volts. (This is a reading of 0.9 V on the multimeter.)
3. Set the DISCRIMINATOR THRESHOLD dial so that the input pulses that are counted have a pulse height significantly larger than the base-line noise and ripple on the signal. (See E.5)
   a. For each pulse that meets the DISCRIMINATOR criterion, the MONITOR output produces a pulse of approximately + 0.45 volts.

4 Oscilloscope Settings – you want the 'scope to trigger on each and every MONITOR pulse.

   a. Reset the Trigger

Type: Edge	Slope: Rising	Coupling: DC
Source: Ch 2	Mode: Automatic	Trigger Level: 200 mV

   b. Sensitivity

Horizontal: 10 ns/div	Vertical Ch 1: 200 mV/div	Vertical Ch 2: 200 mV/div

For each pulse you see on Channel 2, you will simultaneously see, on Channel 1, the actual input pulse which 'fired' the discriminator. ***Importantly, you will see ONLY the input pulses that met or exceeded your discriminator criterion. Their heights will vary, but they will never be less than your chosen minimum value.*** You may also see, to either side of the 'stacked' pulses on Channel 1, lots of low level pulses that did not trigger Channel 2.

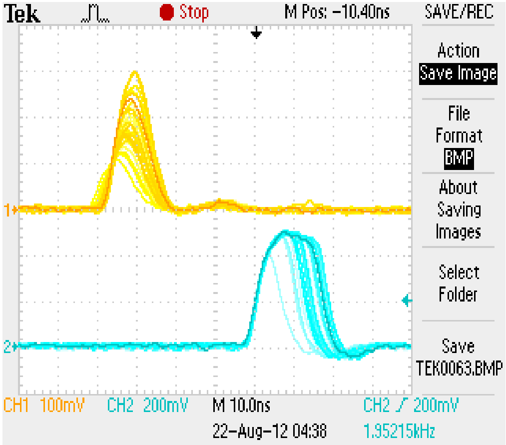
5. Try changing the DISCRIMINATOR to see the effect it has on the pulses that appear on each channel.
   a. Compare the effect on Channel 1 to that on Channel 2.
   b. Turn up the DISCRIMINATOR THRESHOLD until the traces disappear. Why did this happen?

The appearance of the pulse 'stack' on Channel 1 will *change* as you vary the discriminator level. If you raise the threshold condition, the lowest-amplitude pulses on Channel 1 will disappear, raising the 'arch'.

Be sure you understand the meaning of what you're seeing. Be sure to notice both the cause and effect, and the sequence in time of the events you see.

This discriminator function represents the first, and *only*, point in the whole detection chain at which an all-or-nothing or 'digital' criterion is applied to the incoming voltage stream.

You are looking at the very place in your opto-electronic chain where an analog pulse is being assigned a digital, all-or-nothing, significance.



M Pos: -10.40ns

CH1 100mV CH2 200mV M 10.0ns CH2 ⁄ 200mV

22-Aug-12 04:38 1.95215kHz

Fig. 9 Upper Trace: Ch 1, analog pulses going into the INPUT of the PCIT
Lower Trace: Ch 2. standardized pulses coming from the MONITOR

F. Using the PCIT in pulse counting mode.

1. Put the PCIT into pulse counting operation
   a. Initial TWS settings
      - Set the BULB POWER at about mid-scale and note your setting.
      - Set the PMT high voltage on 900 volts
   b. Initial PCIT settings
      - Set the DISCRIMINATOR THRESHOLD dial so that the input pulses that are counted have a pulse height significantly larger than the base-line noise and ripple on the signal. (See section E.5).
      - Set the rotary function selection switch to the COUNT 1.0-s mode.
      - Put the GATE toggle switch in its upward AUTO position.
      - Set the REP RATE dial to mid-scale – this controls the time between measurements.
   c. Expected observations
      - You should see a repeating pattern on the GATE LED. It will turn *on* for 1.0 seconds, and then *off* for a delay-time set by the REP RATE dial.
      - During that 1.0-s of 'gate-open' time, input pulses satisfying the threshold criterion will be counted, giving a rising number on the real-time 6-digit display.
      - Between the intervals of gate-open time, the display will be frozen, and will show the total number of valid pulses that occurred during the previous gate-open interval.

   You now have a real-time indication of the count rate of threshold-satisfying pulses coming from the PMT. These counts, however include the 'dark event' noise we've previously seen.

2. Checking the signal-to-noise ratio* for various discriminator and voltage settings.
   a. Change the PCIT mode to MANUAL and the GATE TIME to 10 seconds.
   b. Determine the signal-to-noise ratio for a PMT bias of 900 V and the discriminator at three different values.
      - Record three ten-second count totals with the shutter open.
      - Record three ten-second count totals with the shutter closed.
      - Determine the average signal-to-noise ratio for each of the discriminator settings.
   c. Change the PMT bias to 700 volts and find the signal-to-noise ratio these same discriminator settings.

Evidently, the signal-to-noise ratio depends on both the discriminator and voltage settings. *In addition, for any given pair of settings, these ratios vary from PMT to PMT.*

In experiments with low photon count rates, it is crucial to have the best possible signal-to-noise. Our bulb, however, produces so many photons that your TWS will show fine interference patterns even with a 'pretty good' signal-to-noise ratio. Section G describes a simple 'rule of thumb' for finding settings that will work well. Appendix A5 describes a systematic way to optimize your own unique PMT.

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* Although we are using the phrase signal-to-noise ratio, in these experiments we are looking for a signal that stands out against a variety of effects other than the standard thermal noise. Here, the 'noise' includes phenomena such as power supply fluctuation, dark current, light leaks and any other miscellaneous causes of fluctuation n the background count.

G. A 'Rule of Thumb' for settings that give a 'pretty good' signal-to-noise ratio.

(This is an alternate way to find a reasonable signal-to-noise ratio for the PMT.)

1. PMT high voltage setting: 900 volts.
   a. PCIT Settings: GATE = AUTO GATE TIME = 0.1s DISCRIMINATOR THRESHOLD = 0.2 turns.
   b. Record three or four sets of counts with shutter open.
2. Increase the DISCRIMINATOR THRESHOLD with shutter open until the count rate has dropped to approximately half. (At this setting dramatically fewer signals will be coming from noise.)
3. Check the signal-to-noise ratio for this voltage-discriminator combination
   a. Switch gate time to 10 s
   b. Record a series of 2-3 counts open and 2-3 counts closed
   c. Find the average signal-to-noise ratio and compare it to the ones you found in section F2.
4. **Record the 'best' discriminator/voltage pair and use it for the rest of your experiments.**

H. Reality checks and other insights

1. Settings:
   - For all trials, keep the voltage and discriminator setting at the values found in section G.
   - Use MANUAL mode with a gate time of 10 s
2. Take one set of shutter open and shutter closed readings.
3. Turn up the bulb intensity with the shutter open.
   - What happens to the count rate?
   - Why does this make sense?
4. Close the shutter and compare the effect to what happened at the lower BULB POWER of part 2.
   - How does this compare to what you found at the lower bulb light intensity?
   - Why does this make sense?
5. Open the shutter. Use the micrometer in the middle of the U-channel to move the slit-blocker so that both slits are blocked. How well does your slit-blocker actually work?

I. Estimations of photon energy and verification of one-photon-at-a-time operation

This section assumes an appropriate chain of PMT > amplifier > discriminator > PCIT electronics as described in the previous sections, and are getting real-time photon-event count rates. The following calculations and observations will introduce you to some of the new features of counting photon events.

1. Estimating how 'dim' a light you are detecting using energy considerations
   a. Assume a bulb-power setting such that the rate of observed photon events is 10^3/s.
   b. The green-light photons being used have the following characteristics:
      - wavelength λ near 550 nm = 0.55 μm
      - frequencies f near = 5.5×10^{14} Hz
      - energies hf near 3.6×10^{-19} J (or 2.3 eV) each.
   c. The power level delivered by the photons being detected is, therefore, $(3.6 \times 10^{-19}\ \text{J})(10^3\ /\text{s}) = 3.6 \times 10^{-16}$ J/s, or less than 0.4 fW (femtoWatts).

2. Using time-in-flight calculations as an indicator of a ‘one photon at a time’ mode of operation
   a. Each photon spends about d/c = (1 m of distance)/(speed c) or about 3 ns of time-in-flight
   b. Successive photons arrive with average separation in time of $(10^3\ /\text{s})^{-1}$ or about 1 ms.
   c. Comparing those two times shows you that the box is *empty* of to-be-counted photons 99.9997% of the time.

The claimed ‘photon efficiency’ of the PMT is only about 5% at these wavelengths, so the ‘true’ number of photons in flight is 20-fold larger than this. And of course there are plenty of other photons emitted by the bulb, and passing through slits, which end up not reaching the PMT’s photocathode at all. Even making allowance for all of these factors, you are *still* in a regime in which photons can be thought of as interacting with the double-slit assembly on a one-at-a-time basis.

J. Initial observations of photon-event counting rates in the Two-Slit apparatus

1. Looking at the scatter in photon count data
   a. Measurement: Write down ten or more results from the counter, obtained under nominally identical conditions. You ought to see *scatter* in the data, the statistical fluctuations to be expected from the detection of random events occurring independently in time. The *size* of that scatter is a subject of study in its own right, and is described in detail in Chapter 8.
   b. While taking data it helps to have a statistically valid prediction for the deviation in the measurements. The deceptively simple ‘formula’ is just $\pm\sqrt{N}$. But just what is N? Interestingly, the amount of expected deviation in individual count measurements depends not on the square root of the average count *rate* but rather on the square root of the total number of counts. An example is shown below.
2. **Suggestions for taking data in light of expected statistical fluctuation**
   a. Take and record a few readings***. Be sure to ignore the first counter reading shown after any changes in parameters.*** Depending upon your time selection, it will include events that occurred as much as 0.1, 1.0, or 10.0 seconds in the past.
   b. Add the ‘keeper’ readings to give an observed count total. Their statistical uncertainty is the square root of that total.
   c. Dividing both numbers by the total count time gives both a count rate, and its uncertainty.

   Example:

   Suppose that when you make a change in the detector-slit position setting with the counter in the 1.0 second automatic mode.

   Let’s assume that the first four numbers you read off the counter are 454, 783, 819, 799. Treating the first of these numbers as a leftover from a previous 1.0-second gate-open time, we find that 3.0 seconds of gate-open time, under stabilized conditions, have given 783 + 819 + 799 = 2401 counts.

   The statistical uncertainty to be assigned to that total is $\pm\sqrt{2401} = \pm 49$ counts, so the count *rate* to be reported is 800 ± 16 counts/second.

   If, however, you had instead taken the average count rate of 800 per second as the source of your scatter calculation, you would have an expected deviation $\pm\sqrt{800} = \pm 28$ counts per second. If you stop and think a moment, you realize that using the average rate in place of N means that you are not taking into account the number of times you have done the measurement, clearly an important factor in the statistics of data collection.)

Having found settings that provide an adequate signal-to-noise ratio, convinced yourself that the signals are coming from bulb-generated photons one photon at a time, and learned how to account for the data fluctuations you will encounter, you are ready to perform two-slit interference, one photon at a time.

Chapter 7. Two-Slit Interference, One Photon at a Time

This Chapter assumes that the two-slit apparatus is aligned as described in Chapter 3 and that you have had experience operating it with the laser-source as in Chapters 4 and 5. It assumes that you are using the bulb-source, and have connected the Pulse Counter/Interval Timer and adjusted both the PMT HIGH VOLTAGE and the PCIT DISCRIMINATOR THRESHOLD for effective single-photon counting.

A. Review

This section reviews what you will need to have set up and working in order to use the Two-Slit apparatus in its 'One Photon at a Time' mode. This check list is provided for your convenience.

1. Required configuration of the system.
   a. Slits arranged as follows: source-slit and double-slit in place; slit blocker set so both slits of the double-slit are open, detector slit at expected location of central maximum
   b. Laser Source moved out of light path
   c. Cover closed and secure
   d. Light source toggle set to BULB.
   e. Shutter open to expose PMT so PMT will function as detector
   f. PMT HIGH-VOLTAGE bias and PCIT DISCRIMINATOR THRESHOLD set as in Ch. 6, Sections F-G.

Procedure IF U-channel must be opened

If ever you need to look or check inside the box, this four-step procedure that will ensure the safety of the PMT against excess light:

- Push the shutter down to close off the PMT from light.
- Turn the PMT HIGH-VOLTAGE 10-turn dial all the way down to 0.00 turns.
- Turn the PMT's HIGH-VOLTAGE toggle switch to OFF.
- At the source end of the U-channel, move the toggle switch from BULB to OFF.

2. Parameters you should have recorded
   a. Code number on double slit that indicates slit spacing (See Ch. 2, Section A.2.)
   b. Five settings of the micrometer controlling the slit-blocker (See Ch. 3, Section F-G.)
3. Configure the PCIT to give you a real-time indication of the count rate of the photon events. A good place to start is as follows
   a. Set the PCIT Function Select dial GATE (s) to 1.0 s
   b. Set the GATE toggle to AUTO and adjust the REP RATE so you can comfortably record data.
   c. Activate the 'cricket' function of the PCIT to get an audio indication of each photon event. It sends out a stream of clicks that sound a bit like the output of a Geiger counter.

B. Things to do before proceeding

1. Adjust BULB POWER to set the count rate.

   It is a matter of choice what peak count rate you will get at the central maximum of the two-slit interference pattern. What parameters will control this count rate? How does the magnitude of the count rate affect the usefulness of the measurements?

   NOTE: As explained in Appendix A3, section C, at any of these count rates, the apparatus can still be said to be in the 'one photon at a time' mode.

2. Record two possible values for the 'background' level of rate of events.
   a. Record count rate with the shutter closed. The shutter closed background or 'dark event' rate from your PMT will depend on its history, its 'personality', and on the voltage-bias and discriminator-level settings you have made.
   b. Record count rate with shutter open, but the slit-blocker set to block light from both slits. In this case, some light inside the U-channel will have been scattered around within the box until it reached the PMT through the open shutter.
   c. Which of these measurements is the best measure of the 'noise' in your experimental data? Ideally, this background rate will be more like 10^1 or 10^2 events per second, and thus constitute a small (1% to 10%) fraction of the total event rate you record.

C. Important ideas to think about as you do these 'single photon' experiments

In the single photon mode of operation, as in LASER mode, there are two main independent variables; the location of the detector-slit (which controls where in the interference pattern you are monitoring), and the setting of the slit-blocker (which controls whether you are getting one-slit, two-slit, or no-slit conditions in your optical bench). There are other variables, including the brightness of the bulb, and the settings of the PMT high voltage and PCIT DISCRIMINATOR THRESHOLD dial, that should already be 'optimized'. These will now stay fixed. There is only one dependent variable, the count rate of photon events arriving at the PMT.*

To get the PMT to produce a 1-dimensional image of the interference pattern, just as with the photodiode, you'll use the detector-slit to pick out one narrow vertical stripe of the 2-d interference pattern, and to pass *only* that stripe of light onwards to the PMT. Then, as you turn the micrometer to scan the detector-slit's aperture across the interference pattern, the amount of light passing onward to the detector ought to vary between a maximum (when the slit is centered on a 'bright fringe') and a minimum (when the slit is centered on a 'dark fringe'). ***The assumption is that the whole pattern is stable in time, so you can record the count rate at various points in the pattern one after another and treat the resulting data as equivalent to recording all the points in the pattern simultaneously.***

If the slit-blocker is set to have both slits open, there should be a two-slit interference pattern existing in space – if interference really does happen on a 'one photon at a time' basis! But keep in mind the dramatic difference between single-photon counting and photodiode detection. At a given location of the detector-slit, photodiode detection involves recording a single voltage on a multimeter. By contrast, the PMT counts have obvious fluctuations. Therefore, you must now devise a strategy for selecting and recording data for these fluctuating numbers. (See Chapter 6, Section J2)

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* Remember, the PMT is *not* a camera, and does *not* perform imaging. Like the photodiode, it is a 'bucket detector' with a photocathode about 8 x 25 mm^2 in size. It registers the total rate of photon-events initiated anywhere on its sensitive area. [There are devices that give real-time indications of the arrival of individual photons in an *xy*-coordinate system, but such '2-d photon imaging cameras' are more than *two orders of magnitude more expensive* than the '1-pixel' device you are using.]

D. Looking for single photon interference patterns

1. Important information: Your micrometer can be set, without interpolation, to successive positions spaced by 1/50th of a full turn. This means that one 'notch' on the micrometer is equal to 1/50th of 0.5 mm, or 0.01 mm. The detector-slit you are moving is about 0.10 mm wide (or 10 notches on the micrometer). How does this affect the way you will take your counts vs. detector-slit location data?
2. Decisions before beginning
   a. By what increments will you change your detector-slit locations?
   b. How will you deal with the genuine fluctuations in the observed count rates?
   c. Finally, you might think about taking a set of measurements with the slit-blocker set to block both slits. What use might that be?

It is crucial that you plot your data set either as you are taking it, or right after you've completed an individual scan, to see if it makes sense as a graph. If you worry about repeatability, you might look into 'backlash' of a micrometer, and might choose to make all you micrometer settings so you approach target locations always from the 'same side'.

E. Explorations

1. Using the PCIT to measure the photon count rates in the 'interference' patterns
   a. Patterns to investigate;
      - 'Far' single slit open
      - 'Near' single slit open
      - Both slits open
   b. How will you deal with the background count rates in these measurements?
   c. Note: The 'Cricket' may be helpful when making your measurements.
2. Does the sum of the single-slit photon count data taken individually equal the pattern found with both slits open? Explain.
   a. Consider the count rate at the central maximum of the two-slit pattern.
      - How does that two-slit count rate compare with the sum of the two single slit pattern count rates found at the same location?
      - You may want to check your data by repeating the three measurements for the central maximum location of the detector-slit.
   b. Consider the count rate at the first minimum to one side of the two-slit pattern. How does this rate compare with the count rates of the single slits at the same detector-slit location?
3. How do the patterns found in these single photon experiments compare with those found in the laser-source/photodiode detector experiments?
4. How can you use your data to determine the wave length of these green photons?
5. What does it mean to determine the 'wave length' of a single photon?

An 'odd' thought: You would surely not be eager to stand before a battery of *two* machine guns aimed at you (rather than just one) on the grounds that their simultaneous operation would *lower* the likelihood of any of their bullets reaching you. But this is the implication of the count-rate data examined in Exploration 2b, and it should undercut your picture of photons-in-flight as particulate 'corpuscles of light'.

The truly novel thing: You computed the wavelength of light *that you were detecting as single photons*. You could not perform this calculation if you'd seen only one photon arrive (why not?), but for the sample that you've taken, and with the maxima and minima you've gotten, you can compute a wavelength.

The harder questions: What is the wave? And if light is a wave, why do the photon events arrive randomly, and independently, as they do? And if light is a particle, and not a wave, how does each photon seem to know about both slits? ***Welcome to the 'quantum mystery'!***

Chapter 8. Theories for One-Slit and Two-Slit Interference

This chapter discusses the theoretical modeling appropriate for the sort of data that can be taken as 'panoramas' of the interference patterns that exist in the detector-slit plane of the Two-Slit apparatus. Remarkably enough, the theories do *not* directly address the question of what light is, but instead make mathematical models of it, and deduce conclusions from these models. For example, the first class of models, the Fraunhofer/Fresnel theory of interference, arose originally as a consequence of an 'ether displacement' model for light, one pre-dating the electromagnetic model of Maxwell's Equations. The second class of models, a Feynman-path calculation, is even less concerned about what light is, or what it is made of, and offers instead a purely mathematical prescription which produces predictions about experiments.

Whatever the model, it needs to be adaptable enough to predict what will result from one-slit, as well as two-slit, geometries. All the models make no conceptual distinction between 'one-slit diffraction' and 'two-slit interference'. These individual phenomena, with their unnecessarily distinct but historically-entrenched names, are manifestations of the same underlying phenomenon. We will interpret the models as giving either the intensity of light (under conditions in which we detect total energy, rather than individual photons), or the average rate of arrival of photons (under conditions in which we do detect individual photons). No model known can predict anything except a probability of arrival of a single photon, and the models are silent about this indeterminacy, which seems to be implicit in the phenomena.

A. Fraunhofer models for interference and diffraction

The simplest models for the data you have now taken are based on the assumptions of Fraunhofer diffraction, and are described in generic textbooks on electromagnetism. Find a reference you like, and compare the assumptions of the theory to the facts of the TWS experimental set up. Here are some things you will notice immediately.

Theory assumes light reaches the double-slit assembly as a plane wave, i.e. from a source infinitely far away. Your light reaches the double slits from the source slit, about 38 cm away.

Theory assumes the double slits are the same width (call it a) and that they have a center-to center separation (call it d). Theory also assumes a 2-dimensional approximation, with the slit lengths indefinite. Your apparatus has slits with approximate values $a \approx 0.1$ mm, $d = 0.353$ mm (for the slits labeled with a '14'), and slit lengths of about 10 mm.

Theory assumes the light is of a definite wavelength λ, In your experiment, the laser light is monochromatic, with λ falling somewhere in the range 0.670 ± 0.005 μm, while the filtered bulb light is not monochromatic but is a distribution of wavelengths over a range from about 0.541 to 0.551 μm.

Theory assumes the light spreads from the double-slit assembly toward a point detector also infinitely far away, so the radiation pattern can be expressed in terms of an angular variable θ, measured in radians away from the central axis of the apparatus. Your detector is not point-like, but is effectively ≈ 0.1 mm wide. Nor is it infinitely far away, but a distance of about 50 cm downstream from the double slits. Nevertheless, it is approximately measuring light intensity as a function of an angular variable. You can make a simple model that relates the theoretical parameter θ to the detector-slit position you can set with its micrometer.

Now find a reference that gives a predicted intensity distribution for a two-slit experiment analogous to

$$I_2(\theta) = I_0 \left(\frac{\sin\alpha}{\alpha}\right)^2 (\cos\beta)^2 \quad \text{where} \quad \alpha = \frac{\pi\, a}{\lambda}\sin\theta \quad \text{and} \quad \beta = \frac{\pi\, d}{\lambda}\sin\theta \quad .$$

The same model can be applied to a one-slit experiment, and it gives the prediction

$$I_1(\theta) = \frac{I_0}{4}\left(\frac{\sin\alpha}{\alpha}\right)^2 \quad \text{where} \quad \alpha = \frac{\pi\, a}{\lambda}\sin\theta \quad .$$

Here, the parameter I_0 describes the intensity at the center of the two-slit pattern. Theory predicts that the intensity at the center of the one-slit pattern will be $I_0/4$. Spend some time graphing these expressions until you understand the role of the separate factors in the intensity expressions. You should also get familiar enough with the derivation to understand why the theoretical prediction changes when one, or the other, of the two slits is blocked.

The theory doesn't pretend to predict the intensity I_0 at central maximum, whether that's in units of photodiode voltage or photon count rate; so you can supply this value to the theory ‘by hand'. The theory also can't know what setting of your detector-slit micrometer corresponds to the location of the 2-slit pattern's central maximum, so you can provide this value 'by hand' as well. With these vertical-scale and horizontal-zero adjustments, you should be able to compare the theoretical predictions for signals as a function of detector-slit position with the experimental data you have taken.

You could even indulge in a bit of optimization of the model for two-slit interference data.

- Does your model predict the fringes of the right height? Change the central-intensity parameter.
- Does your model predict fringes centered about the same center of symmetry as your data shows? Change your central-location parameter.
- Does your model display fringes of the right spacing? Change your slit-spacing parameter, or (if you're sure of the *d*-value), your wavelength parameter.
- Does your model display a fringe *envelope* of the right character? (Look at the intensities of the maxima other than the central maximum.) Try changing your slit-width parameter.
- Does your model include the effects of a distribution of wavelength values? Test the effect of including a range of wavelengths appropriate to your experiment.
- Does you model include the effect of the widths of the source and detector slits? Try to model at least the nonzero width of the detector slit.

By these tests, you will not only learn how the model's predictions depend on its input parameters, you will also learn how well your data constrain values of these parameters.

You might also have taken data for signals obtained with one, or the other, of the two slits closed. What does your Fraunhofer theory predict for these signals? Note that there are now no 'free parameters' at all, since your two-slit data have determined all of them. *Now, overlay the predictions on your data, and have a look at one of the deficiencies of a Fraunhofer model.*

B. Fresnel and other models for interference and diffraction

There are various deficiencies of the simple Fraunhofer models discussed above, some of which show up directly in comparisons with experimental data. This section suggests a more general method for modeling interference and diffraction phenomena, one which is free of some of these limitations. In particular, this model does not require the assumption that source and detector are located 'at infinity'. Even so, it is still not a fundamental electromagnetic calculation, since it fails to consider the polarization of actual electromagnetic fields.

Advanced electromagnetism textbooks suggest a variety of methods for treating diffraction, some based on Huygens' Principle for wave propagation and some based on Kirchhoff's integral for scalar wave fields. Both of these theoretical approaches reveal the crucial role of *phase* and, particularly, of the phase variation of a wave field with respect to position. So crucial is this role of phase that nearly all the features of light's behavior can be captured in a truly remarkable model described in Feynman's book *QED: the strange theory of light and matter*. In this book, Feynman models the behavior of light by considering *only* its phase variation. For a monochromatic wave field with a free-space wavelength of λ, this phase variation is taken to depend on positional displacement Δs according to the complex factor

$$\exp(\frac{2\pi i \,\Delta s}{\lambda}) .$$

More surprisingly, Feynman uses the 'sum over paths' approach, and given light source at P, assigns to another location R a wave disturbance that is just the (complex) sum of the results computed along *any and all imaginable* paths that lead from P to R. Along each path, the overall phase is taken to be the product of all the phase factors for each infinitesimal part of the path. Finally, he supposes that a physical observable, such as the probability of detecting a photon at location R, is given by the absolute square of the complex amplitude computed by the sum-over-paths approach.

Independent of the justification of this model (which emerges naturally from the Feynman picture of quantum field theory), it provides a readily-calculated model for interference phenomena, particularly if we make the daring assumptions that we may use an essentially two-dimensional treatment of the apparatus, and further that we may consider only those paths which proceed in straight lines from one slit to another. A complete sum-over-paths calculation would consider all paths, including curved and even *knotted* paths, exploring all of three-dimensional space!

With these approximations, we can locate slits along a longitudinal central axis, with separation D_1 from source-slit plane to double-slit plane, and further separation D_2 from double-slit plane to detector-slit plane. We can also introduce locations P, Q, and R lying within the apertures of the source, double, and detector slits, respectively, located off the central axis by horizontal displacements x, y, and z. (In the spirit of the 2-d approximation, we ignore altogether the vertical coordinates of P, Q, and R.)

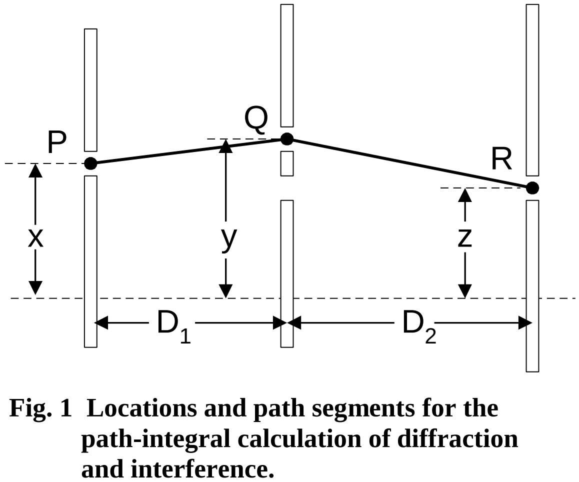

Fig. 1 Locations and path segments for the path-integral calculation of diffraction and interference.

Next, we compute the phase factors for the (assumed straight-line) paths from P to Q, and for Q to R, according to displacements

$$s_1 = \sqrt{D_1^{\,2} + (x-y)^2} \quad \text{and} \quad s_2 = \sqrt{D_2^{\,2} + (y-z)^2} \quad .$$

For a path from source-point P to detector-point R, via intermediate point Q in the double-slit plane, we get an overall phase factor

$$\exp\left(\frac{2\pi i\, s_1(x,y)}{\lambda}\right)\cdot \exp\left(\frac{2\pi i\, s_2(y,z)}{\lambda}\right) \quad ,$$

And, in the spirit of the sum-over-paths approach, we take the overall field disturbance at R to be the generalized sum (here, the integral over all possible *y*-values) over all possible locations for intermediate point Q. This yields the integral

$$I(x,z) = \int_{y\in S} dy\; \exp\left(\frac{2\pi i\, s_1(x,y)}{\lambda}\right)\cdot \exp\left(\frac{2\pi i\, s_2(y,z)}{\lambda}\right) \quad ,$$

In this expression, the domain of integration S is the combination of the two slits: S_1 ranging from (-*d*/2 - *a*/2) to (-*d*/2 + *a*/2), and S_2 ranging from (*d*/2 - *a*/2) to (*d*/2 + *a*/2).

Finally, the absolute square of this integral is taken to be the model for an observable signal, corresponding to the light intensity or the photon detection rate for point detector at *z*, given point source at *x*.

The experimental apparatus, in fact, has source locations spread from $x = -a/2$ to $x = +a/2$, and detector locations spread from $z = t - a/2$ to $z = t + a/2$ (where *t* gives the location, relative to the central axis, of the center of the detector-slit). Thus, final averages over *x* and *z* would account for the nonzero widths of the source and detector slits.

The computational burden of this approach can be reduced by series expansions of the path lengths s_1 and s_2, in powers of the (rather small) off-axis distances *x*, *y*, and *z*; for example,

$$s_1(x,y) = D_1\,[1 + (\frac{x-y}{D_1})^2]^{1/2} \cong D_1\,[1 + \frac{1}{2}(\frac{x-y}{D_1})^2 + \ldots] \quad .$$

Taking only the lowest-order (quadratic) terms in the series reproduces the Fresnel approximation in optics and can be justified for the parameters appropriate to this experiment. [Exercise: compute a typical next-order term, and show that even when exponentiated, it yields only a negligible correction.] This approximation also allows two factors to be removed from the integral above, giving

$$I(x,z) = \exp\left(\frac{2\pi i D_1}{\lambda}\right)\cdot \exp\left(\frac{2\pi i D_2}{\lambda}\right)\int_{y\in S} dy\; \exp\left(2\pi i\,\frac{(x-y)^2}{2D_1\,\lambda}\right)\cdot \exp\left(2\pi i\,\frac{(y-z)^2}{2D_2\,\lambda}\right) \quad ,$$

In this form, it is clear that the two leading factors will disappear upon taking the absolute square. The integration remaining is still daunting, but can actually be performed analytically in terms of the complex error function Erf(x), allowing a reasonably efficient evaluation of the model's predictions, especially in the context of a symbolic-computation program such as Mathematica.

One notable success of this model is that it can produce predictions for the data obtained with one slit blocked merely by performing the integration only over the region S_1 (or only over region S_2). Since the model makes no assumption about small angles, or detector at infinity, it gives predictions not limited by the Fraunhofer assumptions. These predictions more successfully match the single-slit diffraction data readily taken with the TWS apparatus. Nevertheless, this more sophisticated model does not change any qualitative conclusions you have established and makes only the slightest quantitative differences to your predictions. The need for deep thought about duality for light remains just as urgent after the models for its behavior have been improved.

It is worth noting that this Feynman model is *silent* about what the fundamental exponential varying in space really corresponds to. There is not even an appeal to the electromagnetic fields that are supposed to represent light. Instead, the foundations of this model lie in quantum field theory, and the spatial variations represent, mathematically, the variation of these quantum fields. The question of what is actually propagating through the air in your apparatus is not immediately addressed by the mathematics of the theory. The phenomenon might be described as the propagation of a quantum amplitude, whose interpretation is that its absolute square gives the probability of a quantum event. However vague this picture might be physically, it at least both shows that ‘something’ can propagate as a wave disturbance, and predicts the probability of observing an individual photon event. This is perhaps as close to an ‘explanation’ of wave-particle duality as can be achieved by a translation from the mathematical language of quantum field theory into a more mechanical or easily visualized picture.

Chapter 9. Statistical Experiments with Photon Events

This Chapter turns from one-slit and two-slit interference *per se* to a set of experiments that can be done with the apparently random 'event stream' of photon events emerging from the PMT. It presumes you have taken data in the single-photon-counting mode as in Chapters 6 and 7. You will have seen your counter display a series of numbers each representing the total 'number of events' that occur during your selected time interval.

We begin with creating the ideal conditions for delivering such an event stream. After a review of the statistics involved, we then discuss the use of your counter to perform a series of experiments testing various aspects of the claim that the photon events form a 'stationary' but random stream of independent and uncorrelated events.

The first set of statistical experiments involve total counts during a given time interval. The second set of experiments show the random quality of waiting-time intervals between successive photon events. These experiments use the special capabilities of the TeachSpin Pulse Counter/Interval Timer (PCIT) to measure, report, and stream these data to a computer.

A. Optimizing for a steady stream of events

Here are some suggestions for the best optical adjustments of the Two-Slit apparatus to make that series of numbers as useful a statistical source as possible. Within the inevitable 'true statistical fluctuations', you'd like the event stream to be as stable as possible. That means you'd like all *other* fluctuations to be under control. Here are some ways to help:

- Choose a BULB POWER setting at half-scale or lower. That should keep the bulb's real-time aging and dimming as small as possible.
- Have the apparatus aligned optimally so that the light intensity is maximized with respect to any mechanical adjustment. That way, any first-order change in position (say, of a slit) will have only second-order changes in count rate. (See Chapter 5.)
- In particular, if you are in the double-slit mode, be sure you are right at a maximum or a minimum. Operation on the 'side of a fringe' will make you sensitive to micron-scale mechanical distortions of the U-channel.
- Another option is to operate in the one-slit-blocked mode. Because the single-slit diffraction pattern is relatively broad and featureless, the exact detector-slit position will be less critical.
- Make sure you optimize the PMT's high-voltage bias setting. You want to be 'on the plateau', in a region where the count rate is not so very sensitive to any instabilities in the actual high voltage.

All of these suggestions are intended to help keep your count rate 'stationary' in the statistical sense, in particular keeping the underlying mean-value fixed in time.

B. The ‘cricket’ and the Geiger-counter effect

The Cricket function on the PCIT will be helpful for these experiments. When the Cricket is activated, each pulse from the PHOTOMULTIPLIER OUTPUT of the AMPLIFIER MODULE will produce a very brief pulse of sound, a single ‘click’. What you will hear is the aggregate of all of these pulses. When the count rate is low enough, individual pulses will be audibly separable events, a sound effect otherwise heard only from a Geiger counter.

The fact that you hear separate clicks from the Cricket is actually related to the statistics of the events in time. If they were *regular* in time, you’d hear the pulse train as giving a tone with definite pitch. For instance, if there were 100 pulses per second, uniformly spaced in time, you’d have an audio signal consisting of a 100-Hz fundamental and lots of harmonics. But the opposite extreme is what you get here, or from a Geiger counter. The underlying mean rate might be 100 events/s, but the individual events are randomly, not uniformly, occurring in time. The corresponding audible waveform has the frequency spectrum of *white noise.*

The other reason for using the cricket-mode sound output is that your ear is very sensitive to *changes* in the mean rate of arrival of pulses. Importantly, your ear is sensitive ‘immediately’. It does *not need to wait* for the end of a 1.0-s count-accumulation gate-open window in time, followed by a visible display of a total count, to know something has changed.

C. Count-total mean values

Suppose you have a systematic, or automatic, procedure for recording count totals, i.e. transcriptions of successive integer-display readings of the counter in its ‘count totalizing’ mode. With the PCIT, you have the choice of 0.1, 1.0, or 10.0 second gate intervals. Therefore, you *could* form the quotient (count total)/(gate-open interval) to give values of the count *rate*. But all the statistical properties that follow apply *not* to such rates (in dimensions of counts/unit time) but instead to the raw integers, the count totals (which are dimensionless).

Suppose we denote as C_1 the count-total displayed at the end of the first counting interval, and use C_j for the count total at the end of the *j*th counting interval. Repeated trials will produce a whole *set* of data, say $S_A = \{C_j \text{ for } j = 1 \text{ through } n\}$. And you can go right on to form another such set S_B of *n* readings, obtained under apparently identical conditions. Now for each such letter-labeled data set, you can form:

the sample mean $\mu \equiv \frac{1}{n}\sum_{j=1}^{n} C_j$;

the sample standard deviation $\sigma \equiv \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(C_j-\mu)^2}$; and

the standard error of the mean $\sigma_m \equiv \frac{\sigma}{\sqrt{n}}$.

The mean μ gives the average count-total for each data set. The standard deviation σ gives a measure of the typical variation of an individual C_j reading from the mean. And the standard error σ_m gives an estimate for the reliability of the sample mean itself.

D. Standard error and its uses

If you have performed these data-acquisition and data-reduction tasks for two or more data sets (A, B, etc.), then you have a mean for each data set (μ_A, μ_B, etc.), a standard deviation for each set (σ_A, σ_B, etc.), and a standard error for each mean (σ_{mA}, σ_{mB}, etc.)

One use of this information is to test hypotheses. If the entire event-counting process is stable in time ('stationary' in the statistician's sense), then you could hypothesize that the various data-sets' means would agree: $\mu_A = \mu_B$, etc. Of course the actual numerical values you obtain will *not* agree, due to statistical variations. The proper test for stability in time is to see if the difference $\mu_A - \mu_B$ is consistent with zero, statistically-speaking. To do this you will need the propagated uncertainty of that difference, which is given by $\sigma = (\sigma_{mA} + \sigma_{mB})^{1/2}$.

You can now form the significance ratio:

$$\left| \frac{\mu_A - \mu_B}{\sqrt{\sigma_{mA}{}^2 + \sigma_{mB}{}^2}} \right| \quad .$$

Now if that ratio is 3 or smaller, you have certainly not established a genuine difference between data sets A and B. But if that ratio is 5 or greater, you have a 'five-sigma difference' and have established a genuine A vs. B distinction with high statistical confidence.

E. Standard deviation and its expected size

An artificially-constructed data set can exhibit a 'statistical scatter' σ which is zero, or is small, or large, compared to its mean μ. But a data set of raw count totals *for events emerging from a Poisson process* has a predicted value for σ, and the prediction is given by:

$$\sigma = \sigma(\mu) = \sqrt{\mu} \quad .$$

This is a testable prediction, since you are in a position to acquire data sets with mean count μ quite easily varied from order 10^1 to 10^4 or more. You could use a 0.1-s counting interval to get data sets with smaller μ, or a 10.-s interval to get sets with larger μ. Furthermore, you have the option of varying the bulb-source's brightness over another wide range. Thus for each of a series of conditions chosen to give a wide range of mean-count values, you can acquire 2 (or more) data sets, each of 100 (or more) readings. For each individual set:

- Compute μ and σ as before.
- Then, plot (μ, σ) pairs as data points in a scatter plot.

The use of log-log axes is ideal to see if the power-law prediction above, $\sigma(\mu) = \sqrt{\mu} = 1 \cdot \mu^{0.5}$, is consistent with your observations.

Notice that the standard deviation σ for each data set grows in an *absolute* sense with mean count μ, but it shrinks *relative* to μ as μ increases. So for data sets with means near [10, 100, 1000, 10,000], you expect to see growing deviations, near [3, 10, 30, 100]. But these typical deviations, *as fractions of the mean*, are shrinking as [30%, 10%, 3%, 1%]. So if the mean count total is near 10,000, the statistical fluctuations to be expected in the very next single such reading are of order ±100, or ±1%.

F. Chi-squared tests of scatter

You've seen *scatter,* as the differences of count totals in repeated trials under nominally identical conditions. But in addition to such *statistical* fluctuations from count to count, there could also be underlying *systematic* variation. For example, the bulb-source of photon events could undergo a step-change in its brightness, or a slow drift in brightness as it ages. Here are ways to *test* for such non-statistical changes.

Suppose you have a long data set, $\{C_j\}$, of length hundreds to thousands. If the readings C_j were taken sequentially and uniformly spaced in time, then a scatter plot of the pairs (j, C_j) is a plot of observed count-totals as a function of time. Your eye is quite adept at seeing features (real or imaginary!) in such a plot. In particular, you might see evidence of step-changes, or slopes that suggest drifts in time, in such plots. (You can also use such plots to detect obviously-discrepant *outlier* points which arise from equipment failure.)

Here is a non-visual but numerical test of the hypothesis that the underlying event rate is a constant, and that the count-totals in your list are showing no greater statistical fluctuations than those expected from a Poisson process. From the data set, you compute μ and σ as before, and then compute the 'chi-squared sum', a single number serving as a figure-of-merit or measure-of-scatter:

$$\chi^2 \equiv \sum_{j=1}^{n} \left(\frac{C_j - \mu}{\sigma}\right)^2 \quad .$$

If the data passes the test of Section E above, you expect $\sigma = \sqrt{\mu}$, so $\sigma^2 = \mu$, and you can compute instead

$$\chi^2 = \frac{1}{\mu} \sum_{j=1}^{n} (C_j - \mu)^2 \quad .$$

Now χ^2's value will be zero if (and only if) there is no scatter at all, so that each C_j is equal to the sample mean μ. Clearly, χ^2 as defined gets a contribution of +1 to the sum for each C_j which lies ±1σ away from the mean. If that occurred in all n terms in the sum, the total χ^2-value would add up to n. For count-total data subject only to Poisson fluctuations, you will *not* get a contribution of +1 for each term in the sum, but it turns out that you can still expect the χ^2 sum to come out close to n, in the sense that you can expect

$$\frac{\chi^2}{n-1} = 1 \pm \frac{\text{a few}}{\sqrt{2n}} \quad .$$

[You've extracted 1 parameter, the mean μ, from a data-set with n values, so you have a χ^2-test with n-1 degrees of freedom.]

So if, for a list of $n = 100$ count totals, you find the measure of scatter about the mean is $\chi^2 = 90$, you have gotten a 'reduced chi-squared' of $\chi^2/(n-1) = 90/99 \approx 0.91$. This can be compared to the expectation that this quotient would fall into the range $1 \pm (\text{a few})/\sqrt{(2\cdot 100)}$, which is $1 \pm (\text{a few})\cdot 0.07$. Here 'a few' has the usual significance: <3 is no news, >5 stands for a solid indication. For a set of $n = 100$ count-totals, a χ^2-sum under 65 stands for a convincing demonstration of too *little* scatter, and a χ^2-sum over 135 establishes scatter in excess of Poisson statistics.

Actual data sets obtained under real-life conditions can easily show 'too much scatter' by this χ^2 test, even if their (j, C_j) scatter plot looks like normal data, and this would constitute evidence for some non-statistical, i.e. systematic, effect in the apparatus producing the events being counted. Thinking again of the scatter plot of (j, C_j)-pairs, you can see that computing a mean μ corresponds to 'fitting this plotted data' with the model of a horizontal line, and you can also see that χ^2 measures the scatter of the actual data points about this horizontal line at level μ in the plot. But if there were underlying *drift* in the apparatus, a model that would better fit the scattered points in the plot would be a *sloping* line. For a linear model described by $C(j) = m_0 + m_1 \cdot j$, you could compute a new χ^2-sum given by

$$\chi^2 = \sum_{j=1}^{n} \left(\frac{C_j - (m_0 + m_1 \cdot j)}{\sigma}\right)^2 \quad .$$

For a poorly-chosen intercept m_0 and slope m_1, this χ^2 could come out as big as you like. It turns out that the *lowest* value of χ^2 you can get for this sum is to use, for m_0 and m_1, the intercept and slope of the ordinary least-squares best-fit of a line to the set of data.

Now this new model reduces to the old one, in the special case that $m_0 = \mu$ and $m_1 = 0$. With a variable slope parameter newly at your disposal, you are sure with this new model to be able to get a *lower* χ^2-value than you did before. But how *much* lower, that is the question. The new version of the 'reduced chi-squared' is the (new χ^2)/(n-2), as you now have fit 2 parameters to a set of n input points, and have only n-2 degrees of freedom. Again, this reduced χ^2 is expected to fall into the range $1 \pm$ a few $/\sqrt{(2n)}$. If the chi-squared scatter about the mean μ gave too large a reduced χ^2, but the scatter about the best-fit *sloping* line gives a reduced χ^2 that does fall within this range, then you have established two things:

a. the reality of a non-zero slope of the line, with good statistical significance
b. that the scatter around this line is no larger than would be expected on the assumption of Poisson statistics

G. Histograms of count totals

If you have made scatter plots of (j, C_j) pairs, then you've seen plenty of points in the plot near the level of the mean value, but ever fewer points located at heights far above or far below the mean. If you were to project all your points sideways onto the y-axis, and picture them as 'piling up' there, then you would have a vision of a histogram of C_j-values. To form a good-looking and visually-useful histogram, it helps

- to have a rather long list of count-totals, perhaps $n = 1000$ or more C_j values, and
- to have a data set of $\{C_j\}$ values that comes from a stable configuration, one that you've shown does *not* suffer from experimental step-changes or drift.

The essence of a histogram is to 'bin' the individual C_j-values into a set of bins of equal width. The 'bin width' you pick is your choice, but a bin-width choice of order $(1/5)\sqrt{\mu}$ to $(1/2)\sqrt{\mu}$ would work well. There will be individual occurrences C_i which depart from the mean μ by several multiples of $\sqrt{\mu}$, so you'll get 10-20 bins with non-zero contents. Now you form and plot B_k, the number of occasions of C_j-values falling into each bin, as a function of x_k, the coordinate locating the center of each bin.

[Example: if $\mu = 900$, so that $\sqrt{\mu} = 30$, then a good choice for bin width might be 10. Thus there is one bin whose bin-contents value B_k would be incremented, by one, for each occurrence of a C_j-value falling in the range 895-904 (inclusive), and that bin would be assigned an x_k-value of 900. An adjacent bin would be allocated to counting occurrences of C_j-values in the range 905 to 914 (inclusive), and that bin's contents would be labeled by B_{k+1}, and it would be located at $x_{k+1} = 910$. And so on.]

There are software packages which can form histograms for you automatically, given a $\{C_j\}$-list, though it might be harder to get them to use the bin widths, and boundaries, that you prefer. But however you form the histogram, you should then visualize it by making a scatter-plot, or a bar-chart, for (x_k, B_k) combinations. Once you have that histogram depicted, it is very useful to overlay it with a plot of a Poisson (or Gaussian) distribution, plotted as a continuous function of x, and normalized to match the mean, and the number of occurrences, in the histogrammed data. Your eye can be quite proficient at seeing a misfit between the experimental histogram and the theoretical (Poisson or Gaussian) distribution which can be plotted atop it. (Section I. below gives a bit of the theory, which is also covered in any intermediate-level statistics textbook.)

H. Waiting-time intervals between successive photon events

This section requires a special capability of the TeachSpin Pulse Counter/Interval Timer (PCIT), the ability to measure the time between successive photon arrivals.

If you find it natural or obvious that the histograms you have acquired have a Gaussian shape, you are in for a surprise in this section, which exploits the capability of the PCIT, as 'interval timer'. Think back to a stream of randomly-occurring events, which is nevertheless consistent with an average rate of (say) 2000 events per second. In any actual time interval of 1.0 second, there will be about 2000 actual events, separated by [(about 2000) – 1] time intervals, or waiting times, lying between them. This says that the *average* waiting time until the next event is about $(2000/\text{s})^{-1} = 500\ \mu\text{s}$. But what about the *individual* waiting times, say between events #1 and #2, or between events #M+1 and #M+2? These are the values you can capture using the Interval mode of the PCIT.

To see this mode in operation, have the counter running in the pulse-counting mode as in all the previous sections, and set up to give an average event rate somewhere in the vicinity of 10^3 events/s. You must be in the INTERVAL TIMER mode of operation of the counter. The units of the display will no longer be events-count, but instead, time-in-microseconds from one event to its first successor. (Here, as usual, 'event' means an input analog pulse which satisfies the discriminator-threshold condition – these are the same 'events' you've been totalizing heretofore.) For an initial indication of what is happening, use the PCIT first in the MANUAL mode, for which each depression of the spring-loaded toggle switch will give an individual reading of D_i, the 'waiting time', in μs, between the first, and the second, input event which occur following your finger command. Repeat this switch-depressing a dozen times, and write down the D_i -values that you record.

A first reality check on these data is to compute the average, or mean, waiting time you have found. See if that average waiting time is at all consistent with the mean count rate that you have previously established for your event stream. If your previously-observed count rate was near 2000/s, your average waiting time should be near 500 μs.

Next, look at the *scatter* among these dozen values. You should notice two interesting things.

- There is *much* greater scatter among the displayed numbers than the $500 \pm \sqrt{500}$ characteristic spread you've seen in counting experiments, and
- The distribution of D_i-values is *not* symmetrical about the mean: if the mean of $\{D_i\}$-values is 500 μs, you'll see more occurrences in the 250-500 μs range than in the 500-750 μs range.

This is meant to whet your appetite to get *much* longer $\{D_i\}$ lists than you'd care to acquire by hand. That's the motivation for the AUTO mode of the PCIT, where D_i values *cease* to show up on the Counter's display, but appear instead as successive entries in a growing file on a USB-connected computer. In fact, such a list grows *rapidly* – you need only wait (on average) half a millisecond for an event pair, plus a few more ms for data-transfer time, for each D_i-value to be added to the file. Thus *hundreds* of D_i -values can be recorded in each second of real time. Impressively long lists of D_i-values can be accumulated.

[If the PCIT software should 'hang up' after creating a list of finite length, you can get data transfer to resume by hand-toggling the sequence AUTO → MANUAL → AUTO. The computer file should then resume getting D_i values from the same underlying distribution. You can piece together enough segments this way to get a $\{D_i\}$-list of any length you choose. A set of at least 10^4 samples will give interesting results.]

In our example, these D_i-values form a list with a mean waiting time D_{avg}, of 500 μs. In fact D_{avg} should be the reciprocal of the mean count rate, as measured using the pulse-count mode of the counter's operation on the same stream of physical events.

These D_i-values also have a variance, defined by $< (D_i - D_{avg})^2 >$, the mean of the square of the deviation from the average. Unlike the case of count data, where the variance is equal to the mean (so that the standard deviation is equal to the square root of the mean count), here the variance is larger. How *does* the measured variance change as you change the D_{avg} value? (Recall that dimming the bulb gives a lower average count rate, and thus a longer average waiting time.)

There is also a graphical way to see the character of the waiting-time values D_i indexed by i as they are, and that is to make a list of the pairs (i, D_i), and then to make a scatter plot of these pairs. That plot will look *nothing* like the parallel scatter plot of pairs (k, C_k) you previously made of count-total data. Instead of points clustering around a mean at a 'constant height' in the plot, you'll get what will remind you of a snapshot of molecules in a gravitationally-bound model atmosphere, one exhibiting 'thinning at high altitude'.

Finally, and consistent with this scatter plot, these D_i-values can also be displayed in a histogram, where they will display *neither* a Poisson nor a Gaussian distribution. Instead, the histogram will be *exponential*, having a mean of D_{avg}, but a markedly *un*symmetrical distribution about the mean. The *mode*, i.e. the most common occurrence of this distribution, is *zero*. This means that the shorter the waiting time, the more likely its occurrence! For instance, if D_{avg} is 500 μs and your long list has 25 D_i-values falling into the 510-519 μs bin of your histogram, there will be *more* than 25 D_i-values falling in the 260-269 μs bin of the histogram, and *still more* than that many D_i-values falling in the 10-19 μs bin of the histogram. A bit counter-intuitive, isn't it?

You'll need to read about Poisson processes and waiting-time distributions before you can reconcile this frequent occurrence of short waiting times with your knowledge of the statistical *in*dependence of the individual pulse events in your stream of photon detections. That is to say, you will discover that events which are truly random-in-time are *not* 'self-avoiding', and therefore must display a degree of apparent 'clumping'. This is *not* evidence against their randomness, but in fact evidence in support of their statistically-independent occurrence.

I. Poisson processes

Imagine a series of events which occur in time, according to a pair of simple rules:

1. The probability of an event occurring in the next increment of time Δt is given by $\lambda \cdot \Delta t$, plus terms of order $(\Delta t)^2$ and higher; and
2. The probability of an event occurring is *independent* of events that may have occurred in the past.

The first of these says that λ is the probability per unit time of getting an event; the second says that the process is 'memoryless'.

This model is a fair description of processes including radioactive decay, and it's a good model for PMT photon events in the Two-Slit apparatus, *provided* that photons really do reach and fire the PMT in independent and uncorrelated ways.

For the Two-Slit case, illustrative numbers might be $\lambda = 10^3$/s, and an increment of time $\Delta t = 1\ \mu\text{s} = 10^{-6}$ s, so the product $\lambda \cdot \Delta t = (10^{+3}/\text{s})(10^{-6}\ \text{s}) = 10^{-3} = 0.001$.

This tells you that there is a 0.1 % probability of getting an event in any given microsecond (independent of what might have happened in the past). It turns out that λ also gives the expected value of number of events per unit of time. So in any interval of duration *T*, the mean number of events to expect is $\mu = \lambda \cdot T$. Of course, in any one *particular* run of duration *T*, there will be more or fewer than the mean number of events, due to statistical fluctuations. The probability of getting exactly *k* events in duration *T*, when the expected value is μ, is given by

$$P(k;\mu) = e^{-\mu} \frac{\mu^k}{k!} \quad \text{for } k = 0,1,2,\ldots \quad .$$

And it's easy to show that this distribution is:

a. normalized, in that

$$\sum_{k=0}^{\infty} P(k;\mu) = 1 \quad ;$$

b. of mean μ, in that

$$\langle k \rangle = \sum_{k=0}^{\infty} k\ P(k;\mu) = \mu \quad ;$$

c. of variance also equal to μ, in that

$$\langle k^2 \rangle - \langle k \rangle^2 = \sum_{k=0}^{\infty} k^2\ P(k;\mu) - (\mu)^2 = \mu(\mu+1) - (\mu)^2 = \mu \quad .$$

Since a Poisson distribution of mean μ has a standard deviation of $\sqrt{\mu}$, the distribution gets relatively rather 'narrow' for $\mu >> 1$. In practice, for large enough μ (such as for $\mu > 25$), the Poisson distribution over integers *k* can be approximated by a Gaussian distribution over continuous *k*, given by

$$P_g(k;\mu) = \frac{1}{\sqrt{2\pi\,\mu}} \exp\left(-\frac{(k-\mu)^2}{2\mu}\right) \quad .$$

These distributions *P*(of getting *k* events) are just the sort of distributions expected from repeated trials of the pulse-count mode of the PCIT. But that device also has interval-timing capability, which upon repeated trials gives a look at the probability of getting a first-successor event in the interval (T, $T + \Delta t$).

That waiting-time distribution can also be derived from the assumptions for a Poisson process, and it is given by a probability density over the continuous variable T:

$$\rho(T;\lambda) = \lambda\, e^{-\lambda T} \quad .$$

This distribution makes the predictions of

a. normalization, in that

$$\int_0^\infty \rho(T;\lambda)\, dT = 1 \quad ;$$

which says that the next event is sure to happen *some*time;

b. mean value, in that

$$\langle T \rangle = \int_0^\infty T\ \rho(T;\lambda)\, dT = \frac{1}{\lambda} \quad ;$$

which says that the mean waiting time until the next event is the reciprocal of the average rate of events. (Very curiously, because the process is memoryless, that fact remains truly independent of when you commence the waiting time!)

c. variance, in that

$$\langle T^2 \rangle - \langle T \rangle^2 = \int_0^\infty T^2\ \rho(T;\lambda)\, dT - (\frac{1}{\lambda})^2 = \frac{2}{\lambda^2} - (\frac{1}{\lambda})^2 = \frac{1}{\lambda^2} \quad .$$

which says that the variance is given by the *square* of the mean. Thus the square root of the variance, i.e. the standard deviation, is equal to the mean – note well, is *not* given by the square root of the mean.

Thus, for both the count-totals histogram and the waiting-times histogram, you are able to make an overlay which ought to describe the histogram, using no other input information than the observed mean rate of the underlying process creating photon events. The success of either or both of these distributions (derived from the assumptions of a Poisson process) in overlaying the histograms you acquire empirically represents support for, or at least consistency with, the assumption that the photon events are occurring at random and in an uncorrelated fashion.

TEACH
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Instruments Designed for Teaching

TWO-SLIT INTERFERENCE, ONE PHOTON AT A TIME

Appendices, Specifications, and Safety Information

APPENDIX SECTION

SPECIFICATIONS AND SAFETY INFORMATION

Appendix A1. How to Read a Micrometer Drive

Two micrometer screws allow precise mechanical adjustments to the positions of the slit-blocker and the detector slit in this apparatus. You should learn how they work, and how to read their scales. The two micrometers, and the mechanical flexure mounts they drive, are identical.

Each micrometer consists of a very carefully made metric screw thread of pitch exactly 0.50 mm, so that the rotating shaft of the micrometer moves 0.50 mm for each full turn of the screw. The markings on the micrometer are in place so you can

- keep track of the number of turns you've made, and thereby read the position of the shaft's working end to the nearest 0.50 mm; and
- interpolate within a full turn, so that you can finally quote the position of the shaft's working end to the nearest 0.01 mm .

Here's how to read the number of turns.

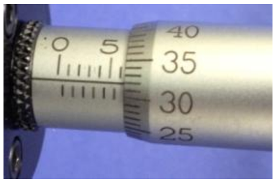
1. Call the fixed part of the micrometer the 'barrel', and the rotating external part the 'drum'.
2. Note that on the barrel there is a printed longitudinal 'stem', along which there are 'branches' emerging alternately on either side.
   - On the one side, every fifth mark is labeled with an integer, 0, 5, 10, and so on: these are at 5-mm spacing, and between them are the 1-mm marks.
   - On the other side of the stem are also branches at 1-mm spacing, but these lie halfway between the mm-marks, and form the 'half-mm' marks.
3. Now turn the drum until the 0-mark on its circumference lies right along the line of the stem (this marks the 0° point on one of its 360° rotations). Find the last branch exposed to view on the barrel, and use it to read the micrometer to the nearest 0.50 mm.

   For example, if the 6-branch and the next branch on the other side of the stem are the last exposed to view, the micrometer is set to 6.50 mm.

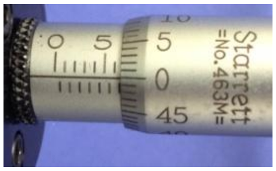
4. Now, from that position, further counter-clockwise rotation of the drum will withdraw the screw, by another 0.50 mm for a full turn.
5. If instead you rotate by a fraction *N*/50 of a full turn, you'll withdraw the micrometer by (*N*/50) x 0.50 mm, or (0.01 x *N*) mm. The drum's periphery is conveniently printed with 50 marks around the circumference, and every fifth one of these is labeled, so that you can read the integer *N* directly.

   This provides the rest of the information you need to read the micrometer to a resolution of 0.01 mm or 10 μm.

6.00 mm



6.32 mm



6.50 mm

6.96 mm

7.00 mm

Appendix A2. Quantitative Detection by Lock-In Techniques

This appendix describes an alternative method for processing the photodiode signal that you used quantitatively in Chapters 4 and 5 of this manual. The advantage is that it will allow you to work with the U-channel open when experimenting in the laser mode without sacrificing accuracy. This approach also offers students a ‘real-life’ introduction to the advantages of lock-in detection.

At the cost of a bit of electronic complexity, lock-in detection offers higher sensitivity to the laser-derived light signal, and immunity from certain kinds of light-induced and electronic background signals. The idea is to isolate that part of the signal due to the laser alone, and to discriminate against any other signals, by turning the laser on and off repeatedly, and electronically isolating the difference that this makes. This technique requires an oscillator with TTL-compatible output to modulate the laser, and a lock-in amplifier to process the photodiode signal.

To use this technique, note that the LASER MOD. input on the source end of your TWS apparatus accepts a TTL-level input (0 to +4 Volt, square-edged waveform) that turns the laser *on* for TTL level ‘high’ (or connector left open) and turns the laser *off* for TTL level ‘low’ (or connector grounded). You can use any signal generator with TTL-compatible square-wave output to drive this modulation input. Modulation rates required are only in the 40 - 400 Hz range.

Within the detector of your apparatus there is a photodiode current-to-voltage converter with its output in the PHOTODIODE section of the detector box. The voltage signal is proportional to the optical power incident on the photodiode. (In addition, there may be a small dc offset in this signal.) The photodiode’s intrinsic response time is well under 1 ms, and the amplifier which turns it sub-µA output current into the voltage you’ve been using has a time constant of 0.4 ms.

If you modulate the laser source, then this photodiode-voltage output will also be modulated in an approximate square wave. You can use lock-in detection of this output voltage, synchronously triggering the lock-in amplifier with the same TTL waveform that is modulating the laser, and thereby achieve total immunity from the DC offset of the photodiode amplifier, and nearly total immunity from all noise signals in the photodiode output. This will permit operation of the apparatus in the quantitative mode with the cover open, and/or higher-sensitivity detection of weaker signals on the photodiode.

Because of the 0.4-ms time constant in the photodiode voltage signal, you should use a laser modulation frequency below 400 Hz in this lock-in mode. Some lock-in amplifiers have a current-mode input, in which case you can send the raw photodiode current directly to the lock-in. This permits somewhat faster modulation. In either case, you’ll want to set the time constant of the lock-in to at least 100 ms, so as to average over many on-off modulation cycles of the laser.

Note that the lock-in technique will do nothing to discriminate against scattered *laser* light that might be reaching the photodiode; nor will it compensate for poor alignment of the apparatus. But given the averaging features and sensitivity of a typical lock-in amplifier, it can markedly improve the signal-to-noise ratio and the dynamic range of your measurements.

Appendix A3. 'Brightness': From Laser to Bulb to One Photon at a Time

This Appendix has the goal of taking the empirical photodiode signals that emerge from the Two-Slit apparatus in its bright-light mode of operation, and coming to understand their size from a more fundamental point of view. One of the outcomes of this Appendix is to show a comparison between the arrival rates of photons in the bright-light (laser-source) and dim-light (bulb-source) modes of operation.

A. How big should the photodiode signals be?

Let's start with normal operation of the Two-Slit apparatus in the laser-source or bright-light mode of operation, in which light reaching the photodiode detector is the quantifiable observable.

Here's a very approximate calculation of how much light might reach the photodiode. Suppose we have the laser on, and it's producing 1 mW of light. Suppose that its beam is centered on the source-slit, and that 1/2 mW or 500 μW of light emerges from the source-slit. That light will spread, due to diffraction through the source-slit, to form a ribbon of width of about 5 mm, so either one of the double slits (each about 0.1 mm wide) will transmit perhaps 1/50th of that, or 10 μW of light. Suppose that only one of the double slits is unblocked, so that 10 μW of light emerges beyond the slit-blocker and diffracts again, to spread out over 5 mm by the time it reaches the detector-slit. Again the detector-slit, of width about 0.1 mm, will pass about 1/50th of that light, or about 0.2 μW, onward toward the detector.

A photodiode (like a solar cell) is a light-to-current converter, and for the red light in question, it will convert light to current with a conversion constant of about 0.5 μA/μW. [This number, in turn, can be explained using a quantum picture of the red light you're using – see section B. below.] We are led to expect a photocurrent of about

$$(0.2\ \mu\text{W})\cdot(0.5\ \mu\text{A}/\mu\text{W}) \text{ or about } 0.1\ \mu\text{A}.$$

You could measure that current directly with a microammeter, but it is easier to convert it to a voltage. The I-to-V, or current-to-voltage, converter you're using with the photodiode has a conversion constant of 22 V/μA, so according to the calculation above, you might expect an output voltage signal of about 2 V in the one-slit-blocked mode. This is the basis of the claim in Chapter 6 that signals of this size are to be expected from a properly aligned apparatus.

B. Photons in the bright-light mode

This section will show you that a typical optical power of 0.2 μW onto the photodiode corresponds to a calculable arrival rate of photons, and will go on with that photon-based calculation to understand why the photodiode sensitivity has the value it does.

When you're in the bright-light mode of operation, the light is visibly red, and of nominal wavelength 670 nm or 0.67 μm. Such light has an optical frequency $f = c/\lambda = 4.5 \times 10^{14}$ Hz, and a computed energy per photon of $E = h f = 3.0 \times 10^{-19}$ J. Now there's a simple quotient, of (energy per unit time) / (energy per photon), which gives (photons/unit time):

$$(0.2 \times 10^{-6}\ \text{J/s}) / (3.0 \times 10^{-19}\ \text{J/photon}) = 0.6 \times 10^{12}\ \text{photons/s}$$

This gives a typical rate of arrival of photons onto the photodiode.

Above, we claimed that the photodiode would respond to this flow of photons by producing a flow of electrons, an electric current, of about 0.1 μA. This 'responsivity' of the photodiode can *itself* be calculated from a photon picture. The assumptions needed are that each photon arriving at the photodiode is absorbed in it, and that each photon absorption leads to the creation of one electron-hole pair in the semiconductor junction. (This is equivalent to assuming '100% quantum efficiency', and actual silicon photodiodes illuminated by red light nearly achieve this limit.) With these assumptions, our 0.2 μW of light, corresponding to a photon flux of 0.6×10^{12} incident photons per second, ought to give an electron flow rate of 0.6×10^{12} electrons per second through an external circuit. As each such electron carries a charge of $-e = -1.6 \times 10^{-19}$ C, we are led to predict a (short-circuit) electric current of magnitude.

$$(0.6 \times 10^{12} \text{ electrons / s})\ (1.6 \times 10^{-19} \text{ C / electron}) = 1.0 \times 10^{-7} \text{ C/s} = 0.1\ \mu\text{A}$$

The result is just as claimed above!

In the TeachSpin current-to-voltage (I-to-V) converter, the potential difference across the photodiode is actively maintained at zero, so the photodiode does operate to give the short-circuit current computed above. The I-to-V conversion constant of 22 V/μA is enforced by the operational-amplifier circuit contained in it, and so the typical 0.2 μW of light, producing 0.1 μA of current, will result in 2.2 V of output signal.

C. One photon at a time?

A typical arrival rate of 0.3×10^{12} photons per second also allows us to form a picture of 'photons in the box'. Clearly, the vast majority of photons produced by the laser do not reach the photodetector at all; our example above showed how a laser output power of about 1 mW turned into a power level at the detector of only 0.2 μW. But even this sub-microWatt flux onto the detector still corresponds to an enormous rate of arrival of photons. The reciprocal of the arrival rate is the average waiting time between arrival of successive photons, and this gives

$$1 / (0.3 \times 10^{12} \text{ photons / s}) = 3 \times 10^{-12} \text{ s between successive photons (on average).}$$

This average separation of only 3 ps, combined with the limited bandwidth of the I-to-V converter, ensures that arrivals of individual photons are *not* registered one-by-one in the bright-light mode.

But there is another computation related to this 'average waiting time', and that is to compare it to the 'transit time', the time a given photon spends in flight getting from the laser source to the photodiode detector. That transit time comes from a (distance)/(speed) ratio, and gives

$$(\text{about 1 m of flight}) / (3 \times 10^{8} \text{ m/s speed}) = 3 \times 10^{-9} \text{ s in flight.}$$

So now we have a picture in which a given photon spends about 3×10^{-9} s = 3 ns in flight, while its successor is incident on the photodiode about 3×10^{-12} s = 3 ps = 0.003 ns later, on average.

It is the comparison of these two times, 3 ns in flight and 0.003 ns average wait, which tells us that there are of order *1000 photons in flight simultaneously* under typical conditions. And these are only the photons destined to reach the photodetector; the total number of laser photons 'in the box' which end up being absorbed elsewhere is about 4 orders of magnitude higher.

But this calculation is also directly relevant to the *dim*-light mode of operation, in which green-light photons emerge from the bulb source, pass through the same slit assemblies, and eventually reach the (photomultiplier-tube) detector. It is perfectly feasible to get good data showing convincing two-slit phenomena with a rate of detected photon events of order 300 per second. That is to say, the average waiting time between detected photon events is about $(300/s)^{-1} \approx 3$ ms (instead of the 3 ps computed above in the bright-light mode). This shows that the rate of photon detections is about *9 orders of magnitude smaller* in the dim-light mode, compared to the bright-light mode.

It also shows that the instantaneous 'count' of photons-in-flight, which was of order 1000 in the bright light mode, comes instead to order 10^{-6} in the dim-light mode. So the proper mental picture of the photons passing through the detector-slit and registering as events on the photomultiplier tube is *not* that of beads on a string, or a snapshot of cars on a highway. Instead, you can contemplate a photon contributing to the eventually-detected count rate as flying for 3 ns, then being detected, followed by an average wait of 3 ms = 3,000,000 ns until the next photon destined to be detected is even emitted at the source.

Thus according to this calculation, there is only a probability of $10^{-6} = 0.0001\%$ of there being even *one* to-be-detected photon in flight in the box at any instant. That is the basis for claiming that the dim-light mode of operation is 'one photon at a time'.

There are caveats about such a calculation. The first point is that photomultiplier tubes do not operate near 100% quantum efficiency; in fact, the PMT in the Two-Slit apparatus has about 5% quantum efficiency for green-light photons. So for every photon detected, there are about 20 more in flight which go undetected. Furthermore, there are lots of photons in flight through the box which do not get to the detector slit. Finally, there are vast numbers of thermal photons in the box, of typical wavelength 10 μm, to which the PMT is totally insensitive. So 'one photon at a time' is a phrase that has qualifications to it.

Yet another possible objection to the 'one photon at a time' idea is the claim implicit above that photons are produced one at a time *and independently* in the (thermal) bulb source, and proceed through the apparatus without interacting or cooperating. There are actually ways to test this independent-arrivals hypothesis, having to do with the statistical measurements that can be performed on the photon events actually detected and registered on a one-by-one basis. They are described in Chapter 9 of this manual.

Appendix A4. Optimizing the Signal-to-Noise* for *Your* PMT

This Appendix describes a systematic way to find the unique combination PMT voltage bias and PCIT discriminator settings that optimize the signal–to-noise ratio for the PMT in your particular TWS apparatus. In the process you will learn a great deal about the vagaries of PMT behavior and see some surprising patterns.

1. Fixed settings
   a. Set BULB POWER at or slightly above midrange. Keep it constant for the ***entire*** series of measurements.
   b. Connect the PMT PULSE AMPLIFIER OUTPUT of the AMPLIFIER MODULE to INPUT on PCIT.
   c. Set PCIT gate time for 10 s.
2. Making measurements
   a. Choose and set an initial PMT bias such as 650 V
      - Set the discriminator threshold so that the input pulses that are counted have a pulse height significantly larger than the baseline noise and ripple on the signal. See Chapter 6, Section E-5.
         - Record 2 or 3 count totals with shutter open
         - Record 2 or 3 measurements with shutter closed
         - Calculate the average signal-to-noise ratio
      - Find the average signal-to-noise ratios for at least four different discriminator settings
   b. Repeat the measurement series for several other PMT voltages up to 900 V
3. Finding the optimum settings
   a. For each voltage setting, graph signal-to-noise ratio as a function of discriminator setting. What patterns do you observe?
   b. What other parameters should be considered other than the absolute signal-to-noise value?
   c. Select the settings that best optimize signal-to-noise for your PMT and justify your choice.

* Although we are using the phrase signal-to-noise ratio, in these experiments we are looking for a signal that stands out against a variety of effects other that the standard thermal noise. Here, the ‘noise’ includes phenomena such as power supply fluctuation, dark current, light leaks, and any other miscellaneous causes of fluctuation n the background count.

Appendix A5. Returning to Laser or Bright-Light Operation

This section describes how you can most easily change *back* from bulb-source, photon-counting operation, to the laser-source mode of the TWS2-A.

1. The first requirement is to make conditions safe for the PMT, and to do so, you should
   a. Close the shutter.
   b. Turn down the PHOTOMULTIPLIER HIGH VOLTAGE dial to 0.0 turns.
   c. Move the PHOTOMULTIPLIER toggle switch to OFF which disables the PMT.
   d. Turn the source switch toggle from BULB to OFF. Now it is certainly safe to open the cover of the U-channel.

2. Changes needed to use the laser

   a. Switch to photodiode detection

      By closing the shutter, you have already lowered into place the photodiode, for light detection in the bright-light mode.

   b. Change to laser source

      Find the metal block holding the laser source (it should be against the far inside wall of the U-channel) and slide it toward you until it comes firmly against a stop. You will be feeling its magnetic coupling to its mount.

   c. When you have the laser block firmly seated against its stops, it will be back on the centerline of the U-channel, and its beam will be adequately aimed along the centerline of the apparatus. But it might not have settled into quite the same position as when you last aligned it.

3. Correcting the alignment.

   Rather than to go through the whole alignment procedure again, we suggest this alternative

   a. Set the source switch to LASER, so the laser comes on

   b. Use a viewing card to spot its output beam and follow it to the source-slit

   c. Now move the card to just beyond the source-slit, to see if the red light is coming through. If not, move the source-slit laterally *just a bit* (< 1 mm will do) until the beam comes through strongly.

   d. Use the card to follow that beam toward the double-slit assembly, and look for the single-slit diffraction pattern on the card. When you have the card just upstream of the double-slit's vicinity, make a final lateral adjustment of the source-slit to optimize the brightness of the single-slit diffraction pattern you're seeing.

   e. You may have ended up moving the source-slit laterally by the order of its width, about 0.1 mm. If you have moved the source-slit, then for obvious geometrical reason there will also be a comparable change in the location of the interference's pattern's central maximum, down at the detector end of the apparatus.

   f. You can now use the voltage output of the photodiode's I-to-V converter as a dependent variable, and the detector-slit's micrometer-adjuster as an independent variable, to re-locate that central maximum.

Appendix A6. How to Change the Bulb in the TWS2-A

This Appendix refers to the incandescent-bulb light source that serves as the ‘dim-light’ source in using the Two-Slit apparatus in its single-photon mode. That bulb produces ‘thermal light’ with the lowest possible degrees of spatial and temporal coherence, but like any other glowing-filament design, it can eventually fail.

To see if the bulb has failed, close the PMT shutter and open the top cover of the Two-Slit’s U-channel. Find the bulb-source block at the source end of the apparatus. Remove the plastic assembly that holds the green-light filter by pulling on the black ‘snout’. Next, move the toggle switch from OFF to BULB and turn the BULB POWER dial to mid-scale. If the bulb is working, you’ll be able to see its yellow-white light emission falling on a viewing card. If there’s no light, then check to see if power is being supplied to the apparatus. There is a small green light on the power-supply unit which indicates that its +15-V output is live. If you have a power-on indication at the supply, but fail to see any yellow-white emission of the bulb source, then, most likely, the bulb has failed.

Here’s how to replace the bulb. Find a 0.050" Allen wrench, and use it to loosen the Allen-head set screw that’s visible atop the bulb-source block, at its left end. When you’ve rotated that screw by half a turn, the bulb socket is loose. Use the metal tab projecting up from it to pull the bulb’s socket leftwards. When you’ve moved it back by about 1 cm, you’ll be able to see the bulb itself.

Pull the socket-and-bulb combination clear of the bulb-source block, taking care not to overstretch the wires connected to the socket. Now unscrew the bulb from its socket, and replace it with a fresh Radion 1768 bulb.

If you want to test the bulb at this point, use the toggle switch and BULB POWER knob to do so. Then reverse the removal process to re-install the bulb-and-socket combination into the bulb-source block. Remember to re-install the green-filter assembly as well, and you should be ready for operation.

The lifetime that you can expect from the bulb depends almost entirely, and very strongly, on the power level at which you operate it. While its lifetime at full power might be only 10^2 to 10^3 hours, it will last basically forever at mid-dial settings of low-power operation.

Specifications for TWS2-A

TeachSpin's Two-Slit Interference, One Photon at a Time

Photomultiplier tube
  Type: Hamamatsu R 212
  Voltage: 0 – 1.1 kV

Interference Filter
  Center Wavelength: 546 nm
  Full Width at Half Maximum: 10 nm

All Slit Widths: 0.09 mm

Double Slit Separations: 0.356, 0.406, 0.457 mm (14, 16, 18 mil)

Slit-Blocker Opening: Approx. 2.0 mm

Laser (Class II): 670 ± 20 mm < 1.0 mW

Light Bulb: Radion 1768 miniature lamp, screw-end

Universal Power Supply:
  Input: 110 – 230 VAC, 50 – 60 Hz
  Output: 15 V DC
  Current: 1 A

Optical Light Path: 1 meter - approximate

Overall Instrument Length: 52 inches

Important NOte: This Laser Module is sold solely as OEM components for incorporation into the customer's end products or laboratory research. The purchaser/assembler shall assume full responsibility to conform the finished product to all government regulations pertaining to manufacture and use of product (including but not limited to Department of Health and Human Services, Food and Drug Administration, center for Devices and Radiological Health and Regulations, Title 21 CFR Chapters).

warning (user safety precaution):

1. This product is Classified as a Class II laser according to CDRH standards.
2. Since a laser beam can be harmful to the eyes, ABSOLUTELY DO NOT look directly in the aperture while the laser is in operation.
3. Be aware of the fact that laser light may easily be reflected off shiny surface and that can be DANGEROUS.
4. For further safety information regarding laser, please refer to ANSIZ1361 standard For The Use of Lasers. You may request this publication by contacting the Laser Institute of America, Tel: (407)380-1553.

R650-1MTS Miniature Laser Diode Module Specifications:

Operating voltage: 3 to 5.0 VDC Regulated.
Operating Current: Max. 40 IDA.

input Connections: common Ground to **Black** Wire
Positive to Red Wire
Modulation to **White** wire, Signal Hi— Laser on
Signal LO— Laser Off
Fora normal operation without the use of modulation, short **White** and **Red** Wires

Laser Diode Output Power: < 1.0 mw

Classification: Class II

Laser Aperture — — - —-

wavelength: eso _+ ionM

input Leads*

OptiCS: Fixed Optics (Focused at 5.5 - 5.7" Distance)

Wiring/installation warnings:

Prior to wiring the laser module, to prevent any permanent damage to tne unit, please pay attention to tne following warnings.

1. Let the power supply run to stabilize prior using its output to supply laser module.
2. Make sure to insulate the input power connection to prevent any accidental contact between the two input power lines, while the laser module is on. **NEVER connect/disconnect power source to the input leads (JACK) with LIVE power leads,** use of reliable On/Off switch is recommended, .on/off switch must be in off position when applying input power. Switch is turned on after connection is completed. Avoid any loose connection or use of alligator wire clips.
3. Do not pull or apply pressure to the input power leads connected to the Laser Module.
4. Do not use unreliable or unregulated power supplies.
5. DO not block air flow to the laser's enclosure.
6. Check the polarity of the input power before you make any connection to input leads. Although this module is equipped with reverse polarity protection, absolutely avoid connecting the input leads with incorrect polarity.
7. Optimum output is achievable under thermally stable and temperature controlled condition.
8. A complete electrical isolation of module from mounting table is required when installing the module. The housing of laser module may be at positive potential, user must be cautious about creating any possible electrical short when mounting the module.

important Note Concerning Modulating Signal:

1. Modulating input Signal's amplitude must never exceed the supplied voltage.
2. Modulating Signal must be noise free without any over shoot or under shoot to prevent any demage to the built in laser diode.
3. when modulating signal is not used, simply connect It to the positive line, (pulled high)

Care and Maintenance:

The laser module is a very sophisticated electronic device and should be treated with care. There are no user-serviceable parts inside and any attempt to take the unit apart will **Destroy** the solid state laser. To clean the lens use clean air pressure or dry cotton swab. DO not use any cleaning solution.

This product has gone through multiple Quality control Tests prior to its shipment. It is guaranteed to be operational at the time of purchase. This product is sold as components only, if proper care is not applied, it may be damaged. Purchaser is fully responsible for its care.

KEEP OUT OF THE REACH OF CHILDREN

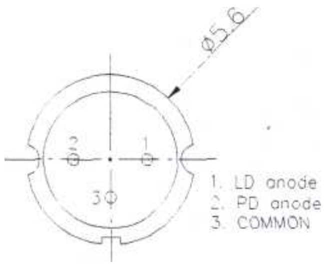
DANGER

LASER **LIGHT - AVOID**
DIRECT **EYE EXPOSURE**

Classli, ClassNa, Class nib
LASER PRODUCTS

MODEL TYPE: VLM-650-00

OUTLINE DIMENSIONS (units: mm)



Bottom View

COMMON

0|

PD

1. **This model integrates optic and laser diode into a solid brass construction, provides an adjustable focus function but without driver circuit.**
2. **Users can adapt their own driver circuit for their professional applications.**
3. **Can be modulated up to 500 KHz.**
4. **The efficiency of collimating lens are 70%, do not laser the module over 3.5mW.**

SPECIFICATIONS	650-00
Operating voltage (Vop)	2.1 - 2.6 V
Operating current (lop) 3mW	40 ± 15mA
Cw output power (Po)	<3mW
Wavelength at peak emission (A p)	645-665 nm
Collimating lens	Aspheric Plastic (<P7)
Housing	Brass
Spot size at 5M	6 ± 2 mm
Divergence	1.6 mrad
Meam time to failure (MTTF) 3mW 25℃	10000 hre
Operating Temp, range	+ 10~ + 40℃