Two-Slit Interference, One Photon at a Time

Operating Manual, version 1 (condensed)

I. Introduction

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 apparatus which makes 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 the 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 which 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 the energy of light in particle-like quanta, in individual photon events. How can light act 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)]

There is a rich historical background behind the experiment 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 1810'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 is very naturally explained in terms of waves. His experiment not only suggested that such 'light waves' existed, it also provided a result that could be used to determine the wavelength of light, measured in familiar units. 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.

And yet 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 which possessed definite and indivisible amounts of energy and momentum. These are very satisfactory explanations so far as they go, but they throw into question the destructive-interference explanation of Young's experiment. 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 sort of questions which lend a somewhat mystical air to the concept of duality.

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 asserts 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 modelling.
2) You will be able to perform the two-slit experiment *quantitatively*, recreating not only Young's measurement of the wavelength of light, but also getting detailed information about intensities in a two-slit interference pattern which 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?]

II. Introduction to the Apparatus

This version of the student manual assumes that your TeachSpin two-slit apparatus is already assembled and aligned. The procedures for assembly and alignment are found in versions 2 (expanded) and 3 (instructor) of this manual.

The apparatus consists of a long rectangular metal assembly, with a single-photon detection box attached to one end. Orient the long assembly on its wooden feet so that the box is at the right-hand end of the assembly, and you'll be properly oriented to match the parts of the apparatus with the descriptions below.

First (before plugging anything in, or turning anything on) you'll need to confirm that the shutter which protects the amazingly sensitive single-photon detector is *closed*. Locate the detector box at the right end of the apparatus, and find the rod that projects out of the top of its interface with the long assembly. Be sure that this rod is pushed all the way *down*; take this opportunity to try pulling it vertically upward by about 2 cm, but then ensure that it's returned to its fully-down position. Also take this occasion to confirm, on the detector box, that the toggle switch in the HIGH-VOLTAGE section is turned *off*, and that the 10-turn dial near it is set to 0.00, fully counter-clockwise.

Now it's safe for you to open the cover of the long two-slit assembly. Before you can do this, you'll need to open the four latches which hold it closed; execute a slight lift and a quarter-turn of each of these latches until they are visibly disengaged. The cover is still light-tight and rather snugly closed, so next position the thumb and fingers of your right hand, applied to the two ends of the left-hand wooden foot of the apparatus, to hold the whole apparatus down against the table. Finally, use your left hand to lift the handle at the far left end of the cover of the apparatus, and pull up until the left end of the cover lifts up by a cm or more.

Once the left end has lifted, use the left-end handle to slide the whole cover sideways and leftwards by a cm or more; this will disengage the right end of the cover from its light-tight slot, so you can lift the whole cover off. [Take this opportunity to learn how to re-install the cover, making sure that you can engage its right end, lower its left end, and re-engage the four latches which hold it in place.]

With the cover open, you are ready to look over all the parts of the apparatus:

- At the left end are two distinct light sources, one a red laser and the other a green-filtered light bulb; also at the left end are the controls for the light sources.
- Found along the length of the long box are the various slits and apertures that form a Young's two-slit experiment. On the front of the box are two 'micrometer drives', which allow you to make mechanical adjustments to the two-slit apparatus.
- Finally, there are two distinct light detectors in the box at the right-hand end of the apparatus:
    - one is called the 'photodiode', which is used with the much brighter laser light source; it's attached to the light shutter in such a way that it's *in position for use* when the shutter is in its *down* position.
    - the other is called the 'photomultiplier tube' or PMT for short, which is used with the much dimmer light-bulb source. **It is safe to use *only* when the cover of the apparatus is in place, and the light bulb is in use; it is exposed to light only when the shutter is in its *up* position.**

Finally, there are electrical connections. Electric power comes from a power module, plugged into your a.c. line and connected by a cable to the left end of the apparatus. Two more cables run from this end to the detector box, and supply the photodiode and PMT detectors with the power they need for operation.

III. Operation of the Apparatus

This section of the manual will introduce you to the functions of the apparatus, leading you through three stages of understanding until you have seen two-slit interference, one photon at a time.

III.A. Visual mode of operation

For this mode of operation, you will be working with the cover of the apparatus open. You will need to use neither light detector, since you will be using your eyes as the only detector needed. You'll be using the laser as light source, and you'll find a supply of business cards or other small white paper screens to be convenient tools.

Use the controls at the left end of the apparatus to turn on the solid-state diode-laser light source -- it's contained within a black metal block. Use a paper screen to find its bright red output beam; the diode laser manufacturer asserts that its output wavelength is 670 ± 5 nm [or 0.670 ± 0.005 μm], and its output power is about 5 mW. [So long as you don't allow the full beam to fall directly into your eye, it presents no safety hazard.]

The laser beam propagates to the right, and it will run into the light-bulb source if that's in its *up* position. So locate the black cylindrical tube which contains the light bulb, and push down the left end of that tube until the whole tube lies flat against the bottom of the box. You'll need to unscrew the adjustable support post underneath the bulb source. Now follow the laser beam until it reaches the entrance slit, or 'source slit', of the two-slit apparatus; this is a single slit, of height about 1 cm, but width of only 0.085 mm. If your apparatus is aligned, the slit will be neatly straddling the laser beam, so that a good fraction of the laser light will be passing through the slit -- use your paper card to see if this is so.

Light passing through this narrow source slit will undergo 'single-slit diffraction', and you can follow this process by moving your viewing card downstream. You will see the red beam spread out horizontally, reaching a width of about a cm by the time it reaches the middle of the apparatus.

In the middle of the apparatus is the holder for the double slit, which is a structure with two rectangular apertures, again each about a cm high, and each with width of only 0.085 mm, and with center-to-center separation of 0.353 mm. [All of the slit structures are mounted on magnetic holders so that they can be removed, examined, and re-positioned; if your apparatus is already aligned, it would be a pity to spoil this alignment by disturbing the slits now.] Instead, put your viewing card just downstream of the two-slit structure, and look (close up!) to see if you can observe the two ribbons of light, just 0.35 mm apart, which emerge from the two slits.

This is your chance to understand the function of the slit-blocker, just downstream of the double-slit system, which will allow you selectively to block the light coming from either of the two slits. This slit-blocker is controlled by the 'micrometer screw' on the front center of the apparatus; rotating the micrometer's knob will move the slit-blocker laterally across the two ribbons of light emerging from the two-slit system. For the present, find a position for the micrometer adjustment which permits the two ribbons of light to emerge and continue rightwards in the apparatus.

Each of the narrow ribbons of light emerging from a slit will continue to diffract; follow these broadening ribbons downstream until they visibly overlap. By the time your viewing card reaches the right-hand end of the apparatus, the overlap will be nearly complete; and you'll see that the two overlapping ribbons of light combine to form a pattern of illumination displaying the celebrated 'fringes' named after Thomas Young. How would you characterize these 'fringes'? Can you describe them qualitatively? Can you distinguish between your description of the phenomenon you see and your hypothesis for its cause?

Now position a viewing card at the downstream end so you can refer to it for a view of the fringes, and take another card back upstream to the vicinity of the slit-blocker. Learn to dial the slit-blocker's micrometer adjuster [the one at the *middle* of the apparatus] until you see how to use it to block the ribbon of light coming from either the farther, or the nearer, of the two slits. Start by rotating the multi-turn micrometer screw fully clockwise, and watch this adjustment push the slit-blocker away from you. Take this opportunity to learn how to read a micrometer dial -- see Appendix A if you haven't done this before -- and now, as you dial the micrometer counter-clockwise, find and record five settings for the slit-blocker's micrometer:

- one position for which both slits are blocked;
- another for which light emerges only from the farther of the two slits;
- a third (anywhere in a wide range) that allows both ribbons of light to emerge;
- a fourth for which light emerges only from the nearer of the two slits; and finally,
- a fifth setting (and highest reading) which again blocks the light from both slits.

It is essential that you are confident enough in your ability to read, and to set, these five positions that you can do so even when the box cover is closed (when you can't, as now, confirm your results by checking with a white viewing card).

Once you've gotten these five settings, let the light reach your viewing card at the far-right end of the apparatus, and find out what happens there, qualitatively, for each of the five settings. In two of them, no light at all will arrive; in the third of them, light will arrive from both slits to form Young's two-slit interference fringes. What happens in the other two cases, when light from only one slit arrives?

In particular, observe what occurs at some *particular locations* on your screen:

- at a bright fringe, or 'interference maximum', what happens to the light intensity when you use the slit-blocker to cover one slit?
- at a dark fringe, or 'interference minimum', what happens to the light intensity *at that location* when you use the slit-blocker to cover one slit?

You should be able to use the language of interfering light waves to describe what you see, and to explain why it happens. You'll be investigating this behavior quantitatively in later parts of the experiment, but for now you need to be familiar with it qualitatively, and in terms of causes.

There's one last piece of the apparatus which you can now learn to use. At the far-right end of the apparatus is a final optical element; it's an exit slit, or 'detector slit', of the same size and character as the source slit, except that it's mounted on a moveable structure like the slit-blocker, so it too can have its position adjusted by a micrometer screw drive. The purpose of this detector slit is to allow light from a narrow slice of the interference pattern to pass along to the end of the long apparatus and into the detector box. By translating the detector slit laterally along the interference pattern in space, you can select which part of the pattern will have its light sent on to the detector. Thus by scanning the micrometer screw of the detector slit, you can scan over the interference pattern, eventually mapping out its intensity distribution quantitatively. For now, ensure that the detector slit is located somewhere near the middle of the two-slit interference pattern.

You are now acquainted with every part of this version of Young's experiment, and with the two 'independent variables' you can control: one is the position of the slit-blocker, and you have recorded settings corresponding to each of five slit conditions; the other sets the location of the detector slit. Now you're ready to go on to quantitative measurements.

III.B. Quantitative mode of operation

This mode of operation of the apparatus continues to use the laser light source, but it begins to use the photodiode detector to survey quantitatively the intensity distribution of the interference pattern, by varying the position of the detector slit. You might conduct these measurements with the box cover open, but room light will contribute excessive and variable contributions to your signals, so now is the time either to dim the room lights or to close up the cover of the apparatus. For convenience, have the slit-blocker set to that previously determined setting which allows light from both slits to emerge and interfere.

The shutter of the detector box will still be in its closed, or down, position. This blocks any light from reaching the PMT, but the shutter in its down position correctly centers a 1-cm^2 solid-state 'photodiode', which acts just like a solar cell in actively generating electric current when it's illuminated. The device is equally sensitive everywhere over its area, so it would record *all* the light in the whole interference pattern if it were not for the detector slit. But with the detector slit at a fixed position, the only light reaching the detector is that from a selected part of the interference pattern; by this means, a single-element, spatially-fixed, large-area detector can serve to record (serially in time) the intensities at various places in the interference pattern. The method of course relies on the fact that the rest of the apparatus is stable in time; happily, the diode-laser source has an output power varying by <0.1% in time, and the mechanical stability of the rest of the apparatus is also adequate.

The electric current from the photodiode is conducted by a thin coaxial cable to the INPUT BNC connector of the photodiode-amplifier section of the detector box. At the OUTPUT BNC connector adjacent to it, there appears a voltage signal derived from that photocurrent. Connect to this output a digital multimeter set to 2-Volt sensitivity; you should see a stable positive reading.

To determine if this reading means anything, go back to the left end of the apparatus and use the 3-position toggle switch to turn the laser source off. This should reduce the voltage signal you've been seeing, but perhaps not to zero; record the value you see, and take it to be the 'zero offset' of the photodiode-detector system. You might turn off the room lights to confirm that the signal you see is actually an electronic offset, and not the leakage of light into your apparatus. The zero-offset reading will eventually need to be subtracted from all the other reading you make of this output voltage.

Turn your laser source back on, and now watch the photodiode's voltage-output signal as you vary the setting of the detector-slit micrometer. If all is well, you will see a systematic variation of the signal as you dial the micrometer; you are scanning over the interference pattern. You'll find a variety of maxima, and you should try to find the highest of the maxima -- this is the 'central fringe' or 'zeroth-order fringe' which theory predicts. Between the various maxima, you should see minima; and if your alignment is good, the signal at these minima should drop nearly to the zero-offset signal you previously recorded. These deep minima are of course the manifestation of destructive interference. The signal at the central maximum should be of the order of 0.5 Volt; if it is much less than this, the apparatus is out of alignment, and insufficient light is reaching the detector.

Before you go on to record data systematically, park the detector slit at the location of the central maximum, and then go over to the slit-blocker micrometer screw, and set it to a (previously determined) reading that you know will permit light to pass through only *one* of the slits. Check what photodiode signal you now are getting -- it should be less than before. Again, set the slit-blocker to permit light only from the *other* of the two slits, and record another diminished signal. Can you explain why the signals have diminished? Corrected by subtraction of zero-offset, by what factor should they have diminished? [Answer: *Not* to 50%, but to a *smaller* fraction, of the original intensity -- why?]

To see another and even more dramatic manifestation of the wave nature of light, set the slit-blocker again to permit light from both slits to pass along the apparatus, and now place the detector slit at either of the *minima* immediately adjacent to the central maximum; take some care to find the very bottom of this minimum. Now you're seeing the effect of destructive interference -- what will happen when you use the slit-blocker to block the light from one, or the other, of the two slits? [Answer: Blocking fully half the light coming through the two-slit assembly is going to *raise* the signal you're looking at -- to what level? and why?]

Once you have performed these spot-checks, and have understood the motivation for them, and the explanation of their results, you are ready to conduct systematic measurements of one dependent variable (the photodiode voltage-output signal) as a function of two independent variables. What you want are three graphs, each giving the voltage-output signal as a function of the detector-slit position; the graphs will be for one slit open, the other slit open, and both slits open. You will want occasionally to block both slits to get a measure of the zero-offset signal which needs to be subtracted from all the readings you take. You will learn, by trying, what spacing of detector-slit positions to use. You will learn this fastest if you, or your partner, plot the data as you take it -- nothing beats an emerging graph for teaching you what is going on.

The data you have obtained are along a calibrated horizontal scale -- if you read Appendix A, you will know what the readings of the detector-slit micrometer imply, quantitatively, for position along the interference pattern. The data are also obtained on a quantitative vertical scale, though this one is in 'arbitrary units' -- we have not translated voltage-output units into light-intensity units, but you may be assured that the (offset-corrected) signal you obtain is linear in light intensity. Thus your data can be directly compared with theoretical models of single-slit diffraction and two-slit interference; section IV of this manual discusses one sort of model which can be used to explain your data. In particular, the spacing of your interference minima and maxima gives a quite direct measure of the wavelength of the red laser light you are using.

III.C. Single-photon mode of operation

If you have gotten the visual and quantitative modes of operation of this apparatus to work, you are ready for this section; but if you have not found interference fringes, trying single-photon detection is not going to cure your problems. So this section assumes

- that you know how to use the slit-blocker, and have left it in position to pass light from both slits; and
- that you know how to find the central maximum of the interference pattern, and have left the detector slit parked to pass light from that central fringe to the detector box.

Now you're ready to go on to the use of the photomultiplier tube, or PMT, which makes available to you electrical pulses that correspond to the detection of light, one photon at a time.

But first a **WARNING**: a photomultiplier tube is so sensitive a device that it should not be exposed even to moderate levels of light when turned off, and must not be exposed to anything but the dimmest of lights when turned on. In this context, ordinary room light is intolerably bright even to a PMT turned off, and light as dim as moonlight is much too bright for a PMT turned on. That is why the PMT box is equipped with a shutter, and the apparatus as a whole is equipped with a buzzer alarm, to help protect the PMT from misadventure. The goal of these safety measures is to assure that the PMT is used

- *only* when its box is coupled to the two-slit apparatus, and
- *only* when the cover of the apparatus is closed, and
- *only* when the light-bulb (and ***not*** the laser) source is being used inside the box.

Before you do anything with the PMT, locate on the detector box the HIGH-VOLTAGE toggle switch which activates its power supply, and ensure that it's turned off; also turn down to 0.00 the 10-turn dial which will later set the voltage that enables the process of electron-multiplication inside it. Also, ensure that the shutter of the box is still in its *down* position.

Now it's both safe and necessary to open the cover of the apparatus, because you're about to change from laser to light-bulb illumination of the two-slit apparatus. When you open the cover, you might find the laser still running; use the 3-position toggle switch to turn it off. Find the light-bulb source (the black cylindrical enclosure) and lift its right-hand end until it's tilted up by about 20° into the air. The thickest, output, end of the source tube is a structure which holds a green optical filter. You should now hold the source tube with your left hand, and use your right hand to rotate and slide that filter-structure off the source tube. (Keep all fingerprints off the glass narrow-band interference filter.) Now turn the bulb power adjustment dial down to 0 on its scale, and set the 3-position toggle switch to the BULB position; dial the bulb adjustment up from 0 until you see the bulb light up.

The humble #47 flashlight bulb you're using will live longest if you minimize the time you spend with it dialed above 6 on its scale, and if you toggle its power switch only when the dial is set to low values.

Now it's time to get the bulb into position to send light along the apparatus in place of the laser source. The goal is to achieve that with*out* changing the position of any of the slits (source, double, or detector slits). To do this, you can use the cylindrical bulb housing as a sort of handle to pull upwards the left-hand end of the bulb housing, until it reaches the height previously attained by the laser beam. (You might even temporarily turn on the laser, and watch its beam strike the rear end of the bulb structure, to achieve this.) Now preserve the height of the left end of the bulb structure, while lowering the right end, until the black tube is approximately level; no great precision is required. Finally, you can re-position the adjustable support structure which holds the light source in position.

To confirm that the bulb is in the correct position, you will need to be able to darken the room completely, and you'll need a dim flashlight and a white paper viewing card. Set the bulb's brightness to about half scale, and follow its splatter of white-light emission to the source slit. Now find the narrow ribbon of light which emerges downstream of the source slit, and trace it along the apparatus in the direction of the double-slit structure. As you travel downstream, the white band will widen horizontally, not only because of diffraction, but also because the filament of the light bulb is extended a few mm horizontally, and the source slit is acting like a one-dimensional pinhole camera. So the ribbon of light will be about a cm wide when it reaches the double-slit holder; what you need to ensure is that this cm-wide stripe of light is on-center in the apparatus and is thus falling on the double-slit structure.

If the cm-wide ribbon is off-center and entirely missing the slits, you will need to go through the alignment procedure discussed in versions 2 and 3 of this manual. But if the ribbon illuminates both slits, you're all set; it is not necessary that it be perfectly centered in the apparatus.

Now carefully put the green filter-holding structure onto the right-hand, downstream end of the light-bulb source, being sure not to disturb the position of the left-hand, bulb-holding end of the structure. The green filter blocks nearly all the light emerging from the bulb, allowing to pass only wavelengths in the range 541 to 551 nm. This is a small fraction of the total light, and while you will now be able to see a ribbon of green light emerging from the source slit, you will probably not be able to follow it very far downstream. No matter; plenty of green-light photons will still be reaching the double-slit structure -- in fact, you should now dim the bulb even more, by setting its intensity control down to about 3 on its dial.

You may now return to ordinary room illumination, and you must close up the cover of the box. Be sure that first the right end, and then the left end, of the cover are fully engaged, and then that all four latches are in place. Now, and *only* now, are you ready to start activating the photomultiplier tube (PMT) to detect the photons that are flying through the box.

200mV/div

You'll need a reasonably fast (>20 MHz bandwidth), preferably digital, oscilloscope for first examination, and a digital counter sensitive to TTL-level (+4 V positive-going) pulses for eventual counting, of photon events. Set the 'scope to about ~~50~~ mV/division vertically, and 200 ns/division horizontally, and set it to trigger on positive-going pulses of perhaps >~~20~~ mV height. >100mV Now find the PHOTOMULTIPLIER OUTPUT of the detector box, and connect it via a BNC cable to the vertical input of the 'scope; use a 50-Ω termination at the 'scope. You are about to look at pulses, each of which starts with the light-induced ejection of a single electron from the light-sensitive photocathode of the PMT. Those photoelectrons will be amplified by about 10^5 inside the PMT, and arrive as a pulse of about 10^5 electrons, or about -2×10^{-14} Coulombs, at the input of a charge-sensitive amplifier. That device will convert that pulse of negative charge to a positive-going voltage pulse, which you will see on the 'scope.

When you are ready with these electronics, keep the shutter closed, set the HIGH-VOLTAGE 10-turn dial to 0.00, and turn on the HIGH-VOLTAGE toggle switch. You are now ready to start dialing up the high-voltage supply which provides the potentials inside the PMT needed for the electron-multiplication process; watch the 'scope display as you start to dial up the voltage, about a turn at a time. [Each full turn raises the PMT 'bias' by about 100 Volts, and the 'gain' of the PMT grows exponentially with this voltage setting. A pair of terminals on the panel allows you to monitor the potential difference (PMT bias/1000) using an ordinary digital multimeter.] As you raise the bias voltage, you will see occasional transient electronic noise, but the 'scope display should be quiet at each steady voltage. Somewhere around a setting of 4 or 5 turns of the dial, you should get occasional positive-going pulses on the 'scope, occurring at a modest rate of 1-10 per second.

- If you see some sinusoidal modulation of a few mV amplitude, and of about 200 kHz frequency, in the baseline of the PMT signal, this is normal.
- If you see a continuing high rate (>10 kHz) of pulses from the PMT, this is *not* normal, and you should turn down, or off, the bias level and start fresh -- you may have a malfunction, or a light leak.)

If you see this low rate of pulses, you have discovered the 'dark rate' of the PMT, its output pulse rate even in the total absence of light. You also now have the PMT ready to look at photons from your two-slit apparatus, so finally you may open the shutter (by grasping that vertically-emerging rod and lifting it a few cm). The 'scope should now show a much greater rate of pulses, perhaps of order 10^3 per second, and that rate should vary systematically with the setting of the bulb intensity.

If you can see those analog pulses, you are ready to look at the digital pulses they trigger. Inside the PMT pulse amplifier is a pulse generator which emits, at the OUTPUT TTL connector, a single pulse, of fixed height and duration, each time the analog pulse you're viewing exceeds an adjustable threshold. Arrange another BNC cable, also terminated at its far end, to a second vertical channel of your 'scope, this one set for 2 V/div vertically. Now start with the discriminator control on your PMT box set to 0, and watch the 'scope display the analog, and TTL-level, pulse outputs in dual-trace operation. You should be able to find a discriminator setting, low on the dial, for which the 'scope shows one TTL pulse for each of, and for only, those analog pulses which reach (say) a +50-mV level.

- If your analog pulses are mostly not this high, you can raise the PMT bias by half a turn (50 Volts) to gain more electron multiplication.
- If your TTL pulses come much more frequently than the analog pulses, set the discriminator dial lower on its scale.

Now send the TTL pulses to a counter, arranged to display successive readings of the number of pulses that occur in successive 1-second time intervals. These represent photon-induced events (which are converted in the PMT to photoelectrons, then multiplied to electron pulses, then amplified to voltage pulses meeting a threshold criterion). *Because of the <100% efficiency of the PMT, not every photon is detected; but you are seeing a representative subset of events due to the arrivals of individual photons.*

To confirm that this is true, record a series of 'dark counts' obtained with the light bulb dialed all the way down to 0 on its scale. Now choose a setting that gives an adequate photon count rate (about 10^3/second) and use the slit-blocker, according to your previously obtained settings, to block the light from both slits. This should reduce the count rate to a background rate, probably somewhat higher than the dark rate. Next, open up both slits, and try moving the detector slit to see if you can see interference fringes in the photon count rate. You will need to pick an detector-slit location, then wait for a second or more, then read the photon count in one or more 1-second intervals, before trying a new detector-slit location. If you can see maxima and minima, you are ready to take data.

A first sort of data will enable you to be assured that you have set the PMT bias voltage to a suitable range. For this data, the independent variable is the PMT voltage setting, or one of its surrogates, the 10-turn dial setting (1.00 turn = 100 V of bias) or the monitor voltage (0.10 Volts = 100 V of bias). The dependent variables are both count rates as read by the TTL counter: one is the count rate at the central maximum of the interference pattern, with both slits open; the other is the dark rate, the count rate obtained under identical conditions but with the PMT shutter closed. Try recording both rates over the range 300 - 650 V of PMT bias, and plot the two count rates on a semi-logarithmic graph. You should see the 'light rate' reach a plateau, with the interpretation that you have reached a PMT bias which suffices to allow each genuine photoelectron to trigger the whole chain of electronics all the way to the TTL counter; you should also see the (much lower) 'dark rate' also rising with PMT bias. See if your graph motivates a setting at which you are counting substantially all of the honest-to-goodness photon events, but minimizing the number of 'dark events'.

Hereafter you may leave the PMT bias fixed, and you may set the bulb intensity to yield some convenient count rate (10^3 - 10^4 events/second) at the central maximum. You are now ready to take just the same sort of data as in part III.B. of this manual, except that now the dependent variable is photon count rate. You'll record this as a function of detector-slit position, making records for three cases: one slit, the other slit, and both slits open. You'll also need to make occasional readings with both slits blocked, to establish a 'background rate' of photons reaching the detector but not passing through either of the two slits.

Your graphs will again have a calibrated horizontal axis of known scale; this time their vertical axis will be in absolute units, of photon events detected per unit time. It is perfectly true that the PMT is not 100% efficient; in fact, for green light, it produces countable electronic events for only about 4% of the incident photons. Now take your central-maximum reading for the event rate, and use this efficiency estimate to infer the rate of arrival of all photons at the photocathode of the PMT. From this arrival rate, compute the average time interval between the arrivals of successive photons. Next, compute the 'time of flight' of a photon in the apparatus, the time it takes to traverse the distance from the bulb source to the detector. Comparing the time of flight of a given photon to the typical time interval between the arrival of successive photons, you can compute the fraction of the time there is even one photon in flight through the apparatus. What is this fraction for your data? This fraction measures numerically the sense in which the apparatus allows you to work 'one photon at a time'; and yet even at this low rate of photons, you can see phenomena that you attribute to constructive and destructive interference. The agonizing question is -- interference of what, with what?

When you have graphed your data, you'll be able to see a number of new phenomena. First of all, from the spacing of the interference maxima, you'll be able to see immediately that the light in question has a different wavelength than the red laser light you used previously. Second, you'll be able to find detector locations at which you can *raise* the photon arrival rate by *closing* one of the slits. Here you'll be in the closest possible contact with the central question of quantum mechanics: how can light, which so clearly propagates as a wave that we can (with this very apparatus) measure its wavelength, also be detected as individual photon events? Or alternatively, how can individual photons in flight through this apparatus nevertheless 'know' whether one, or both, slits are open, in the sense of giving photon arrival rates which *decrease* when a second slit is opened? A good oral dialog between advocates of 'wave-nature' and of 'particle-nature' for light, each using experimental evidence to poke holes in the other's assertions, will do a great deal to teach participants why concepts as slippery as duality have had to be invented.

IV. Theoretical Modelling of 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 now compare the assumptions of the theory with the facts of your experiment:

Theory assumes light reaches the double-slit assembly as a plane wave, ie. 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 $a = 0.085$ mm, $d = 0.353$ mm, 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 somewhere in the range 0.670 ± 0.005 µm, while the filtered bulb light is not monochromatic, but is distributed 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 0.085 mm wide; nor is it infinitely far away, but a distance of about 50 cm downstream. Nevertheless, it is approximately measuring light intensity as a function of an angular variable; make a 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 analogous to

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

Get some practice graphing this expression, until you understand the role of the two factors in the intensity expression; also, get familiar enough with its derivation that you can understand how the theoretical prediction changes when one, or the other, of the two slits is blocked.

The theory doesn't pretend to give 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. But with these vertical-scale and horizontal-zero adjustments, you should be able to intercompare theoretical predictions and experimental data for signals as a function of detector-slit position.

You could even indulge in a bit of optimization:

- 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 these parameters' values.

You 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; so overlay the predictions on your data, and have a look at one of the deficiencies of a Fraunhofer model.

There are much more sophisticated theoretical models than this one, and versions 2 and 3 of this manual discuss some of them. In particular, you can find there discussion of Fresnel-diffraction and sum-over-paths models which avoid some of the approximations made above. Nevertheless, these more sophisticated models do not change any qualitative conclusions you have established, and they make 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.

V. Conclusions

You have performed the two-slit experiment in three ways, and are now fully familiar with the apparatus required to perform it, the data which result, and the simplest models that explain the data. You might even have some numerical conclusions, or deduced values for experimental parameters. But apart from this, you have some added insight into light's propagation and detection.

What is the best evidence your experiment provides that light has a wave-like nature?

What is the best evidence your experiment provides that light has a particle-like nature?

What is the concept of duality, and why was it invented?

Does duality satisfy you, or is the behavior of light paradoxical? Or, is it the character of your *description* of light that is paradoxical?

Appendix A. 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, and you should learn how they work, and how to read their scales. The two micrometers, and the mechanical flexture 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 advances 0.50 mm for each full (clockwise) 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. Call the fixed part of the micrometer the 'barrel', and the rotating external part the 'drum'. 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 labelled 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. 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 5-branch and the next branch on the other side of the stem, are the last exposed to view, the micrometer is set to 5.50 mm.

Now from that position, further counter-clockwise rotation of the drum will withdraw the screw, by another 0.50 mm for a full turn. If 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 labelled, so that you can read the integer N directly. This provides the rest of the information you need to read the micrometer to 0.01 mm.