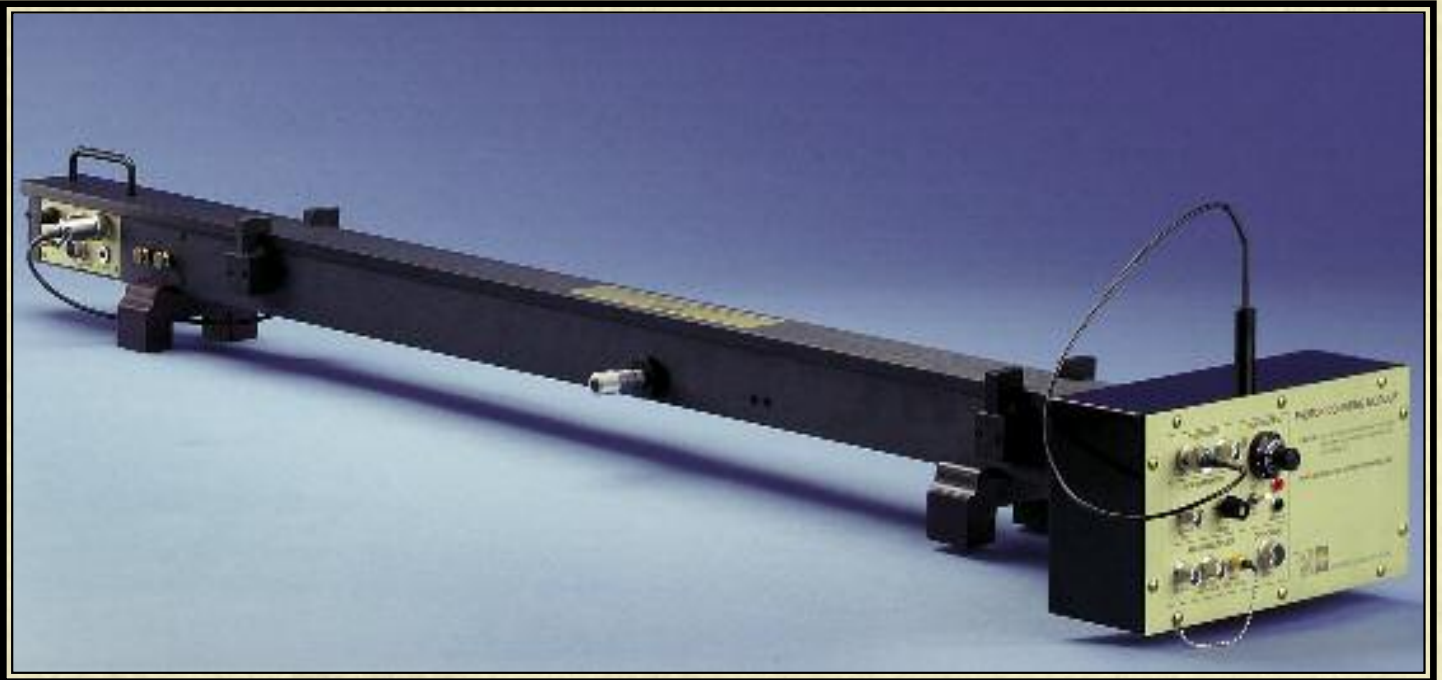


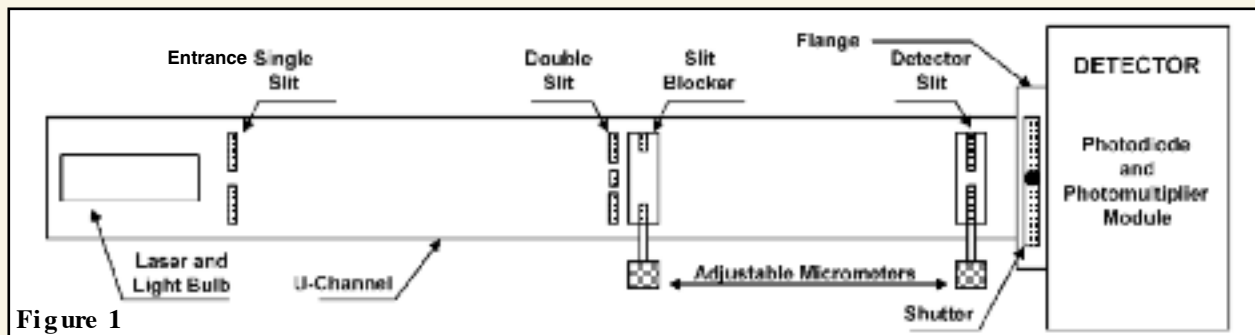
TWO-SLIT INTERFERENCE, ONE PHOTON AT A TIME



The Essential Quantum Paradox

- Perform Two-Slit Interference with Single Photon Source and Detector
- Recreate Young's Two-Slit Measurement of the Wavelength of Light
- Make Visual Observations of Two-Slit Interference
- Explore Photon Counting Optimization
- Compare and Contrast Two-Slit and Single-Slit Interference
- Amplitude Modulation of Laser Source for Lock-In Detection
- Wave-Particle Duality, in the Student's Hands

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INTRODUCTION

Pick up any book on quantum or modern physics and you are sure to find a discussion on the “wave-particle duality.” What is this mysterious duality? Why should anyone, especially a student, believe that this duality is real? TeachSpin has built an apparatus that allows students to encounter duality with photons, the quanta of light.

With this instrument, students perform the seminal two-slit interference experiment with light, even at the limit of light intensities so low that they can record the arrival of individual photons at the detector. That raises the apparent paradox which has motivated the concept of duality: in the very interference experiment which makes possible the measurement of wavelength, one observes the arrival of light energy in particle-like quanta, individual photon events. How is it possible for light to propagate as if it were a wave and yet be detected as if it were a particle? This paradox is the central theme in Richard Feynman’s introduction to the fundamentals of quantum mechanics:

“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 . . . In telling you how it works we will have told you about the basic peculiarities of all quantum mechanics.”

It is the purpose of this apparatus to make the phenomenon of light interference as concrete as possible, and to give students the hands-on familiarity which will allow them to confront *duality* in precise and operational terms. When they have finished, students might not fully understand the mechanism of duality - Feynman asserts that nobody really does - but they will certainly have had direct experience of the phenomenon itself.

THE INSTRUMENT

The instrument consists of a black anodized aluminum U-channel, a little over a meter long, with a removable light-tight cover (Fig. 1). Students select one of the two light sources: a 670 nm, 1mW laser or a flashlight bulb. The detection system is either a photodiode, or a complete photon counting module.

In front of the two light sources is a single entrance slit. With either the laser or the light bulb illuminating this slit, the central maximum of the slit’s diffraction pattern is aligned to cover a double slit assembly about 40 cm down the U-channel. Just past the double slit, a movable slit-blocker can be actuated manually via a micrometer mounted on the outside of the U-channel. Using this slit-blocker, students can compare the light pattern created by the double slit with the patterns created by either of the single slits. Three double slit assemblies, each of distinct slit spacing, are included.

At the far end of the U-channel is a movable single slit, the detector slit. It too is attached to a translational stage actuated by a micrometer. Students move this slit across the interference pattern, in front of either the photodiode or the cathode of a photomultiplier, to make quantitative measurements of either the light intensity or the photons’ arrival rate, as a function of position.

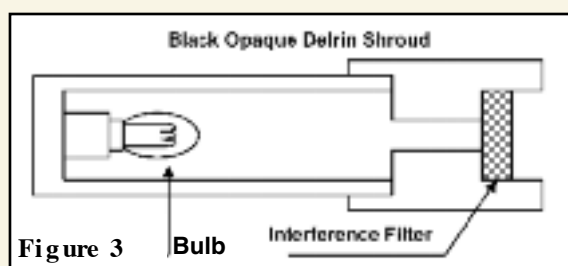


Figure 2

STUDENT EXPERIMENTS

The black box with the brass front panel contains a complete photon counting module, as well as a photodiode detector connected to a current-to-voltage converter. The front panel is shown in Fig. 2. The box is supplied with a special flange and a light shutter. The photodiode is mounted on the outside of the shutter so that it is in the light path when the shutter is closed, and removed from the light path when the shutter is opened to let the light pass to the photomultiplier. The photomultiplier's high-voltage supply and pulse-height discriminator level are both controlled and monitored from the front panel. It is also possible to inject a test pulse to calibrate the charge-sensitive preamplifier.

The entire photon-counting module can be detached from the U-channel and operated independently (requiring only a 15 volt regulated dc supply). This unit is thus available for other applications in the teaching or research laboratory, such as low intensity spectroscopy or photon correlation experiments.



The single-photon light source (Fig. 3) consists of a #47 flashlight bulb connected to a variable voltage-regulated power supply. The bulb is housed in a black plastic tube with a removable narrow-band green interference filter at its output end. Although such bulbs generate about 10^{16} photons per second in ordinary use, operation at reduced power not only lowers the total production rate of photons, it also shifts their distribution toward longer wavelengths, thereby markedly reducing the production rate of “green” photons. The result is a thermal source of randomly produced photons, capable of giving a photon event rate at the detector in the range of $10^1 - 10^5$ per second. Thus, it is easy to take data in the “one photon at a time” regime in which the average waiting time for the next photon event vastly exceeds the time-of-flight for a photon through the apparatus.

The TWS1-A apparatus allows students to experience optical interference three ways. First, after the slits have been aligned, they can use the laser source to observe two-slit interference patterns plainly visible on the white viewing card. In subdued light, they can easily see the distinct differences between the interference patterns from single and from double slits, while learning to use the slit-blocker. These observations are essential for a clear appreciation of the next sets of measurements, in which the cover is closed and the apparatus appears more like a “black-box.”

Second, students repeat the first set of measurements, but this time with the U-channel covered, with the laser as the light source, and with the photodiode placed in the optical path. In Fig. 4, we show the data obtained in this realization of Young's classic experiment. As a function of the position of the detector slit, we plot the output voltage from the current-to-voltage converter connected to the photodiode. Lines are drawn merely to guide the eye.

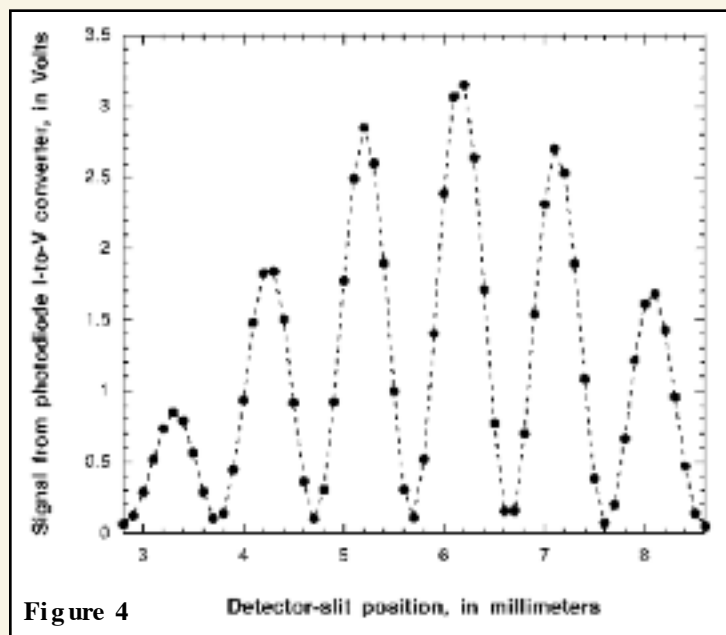


Figure 4

These data can be compared to different theoretical models of the two-slit phenomenon. The simple Fraunhofer model reproduces most of the major features, but the more sophisticated Fresnel integral or Feynman's “sum over paths” can give students greater depth of understanding. Both are carefully discussed in the instructor's manual.

The third method of observing this two-slit interference uses the photon counting module. This requires that the U-channel be closed and completely light-tight with the light bulb as the source and the shutter to the photomultiplier open. In order to optimize the operation of the photon counting unit, students must properly set the high-voltage and the pulse-height discriminator. With the discriminator level fixed, both the count rate for dark current (both slits blocked or shutter closed) and the count rate for “green” photons can be measured as a function of photomultiplier high-voltage. The data shown in Fig. 5 indicates that a setting near 550 V is optimal.

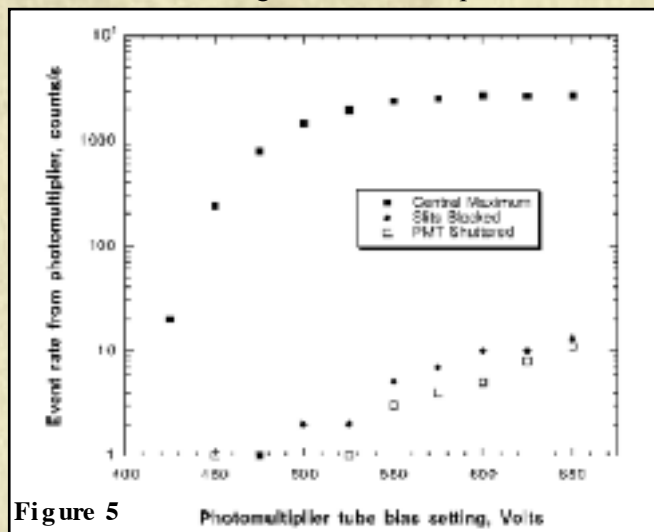


Figure 5

With the photon counting unit set for optimum detection, and the discriminator output connected to a counter, the interference pattern can be observed, one photon at a time. The data are shown in Fig. 6.

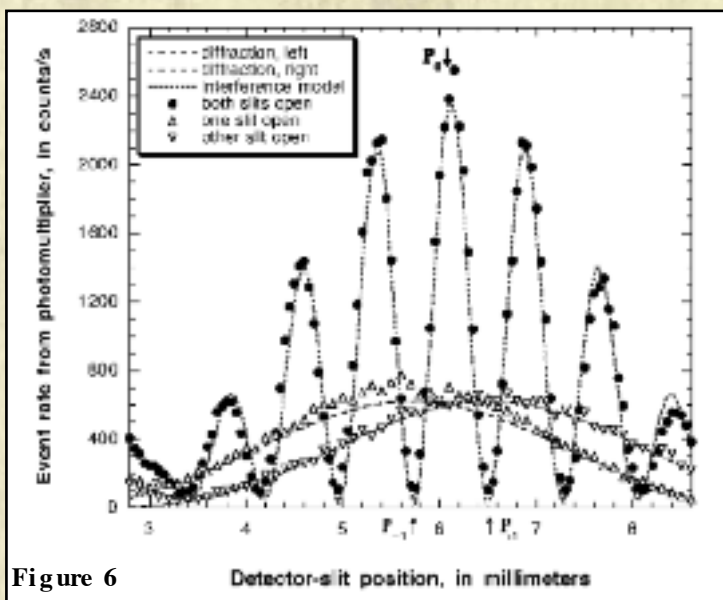


Figure 6

The ‘essential quantum paradox’ can be shown dramatically by a simple experiment (Fig.7). The detector slit is positioned, in turn, at the three empirically determined positions of the -1 minimum, the central maximum, and the +1 minimum of the interference pattern (marked in Fig. 6 as P_{-1} , P_0 , and P_{+1}). Photon count rates are measured for the slit-blocker set to permit light to pass through only one slit, through both slits, or through only the other slit. At the central maximum, going from one to two slits *quadruples*, not doubles, the count rate. And, contrary to the logic of classical particles, at either minimum, opening a second slit markedly *reduces* the count rate!

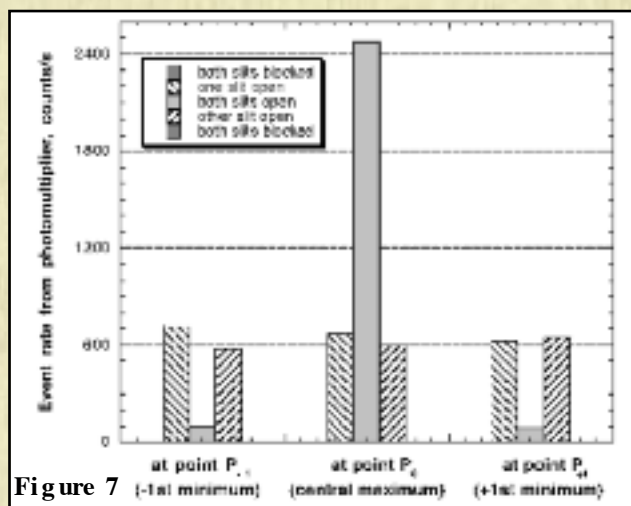


Figure 7

By injection of a TTL signal, the diode laser is modulated so that lock-in detection of the photodiode signal becomes possible. Because of the noise rejection of lock-in detection, sensitive quantitative measurements of the laser-light interference signal can be achieved even with the U-channel uncovered. TeachSpin’s Signal Processor/Lock-In Amplifier is ideal for making these measurements.

SPECIFICATIONS

Photomultiplier tube: Hamamatsu R 212
 Preamplifier-Discriminator: Amptek A-111
 Interference Filter: 546 nm, 10 nm FWHM
 All Slit Widths: 0.09 mm
 Double Slit Separations: 0.35, 0.40, 0.45 mm
 Laser (Class II): 670 ± 20 nm <1.0 mW
 Universal Power Supply:
 Input: 110 – 230 VAC, 50 – 60 Hz
 Output: 15 V DC
 Optical Light Path: 1 meter
 Overall Instrument Length: 52 inches

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