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students interested in photography and art. Holography offers a good way of involving them in some potentially scientific explorations.

The author wishes to thank the many students whose involvement has contributed to the success of the experiments described.

[1] My thanks to Springfield Camera, Inc., Springfield, Ohio.

[2] For general information on these and other aspects of holography see K. S. Pennington, Sci. Amer. **218**, 40 (February 1968) and J. W. Goodman, *Introduction to Fourier Optics* (McGraw–Hill, New York, 1968), Chap. 8.

[3] M. P. Givens, Amer. J. Phys. **35**, 1056 (1967).

[4] M. Young, Amer. J. Phys. **37**, 304 (1969).

[5] C. L. Strong, Sci. Amer. **216**, 122 (February 1967).

[6] L. T. Long and J. A. Parks, Amer. J. Phys. **35**, 773 (1967).

[7] R. Fisher, G. Forrest, E. Gaglardi, and P. Merchant, Amer. J. Phys. **38**, 266 (1970).

[8] Microscope holograms of static objects are also useful. For information on taking these holograms, see G. W. Ellis, Science **154**, 1195 (1966).

# A Single-Photon Double-Slit Interference Experiment

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*We describe a double-slit interference experiment suitable for a beginning physics laboratory in which single photons are observed to interfere with themselves, directly demonstrating the wave–particle duality. When the photons are tagged to indicate which slit they passed through, the double-slit interference vanishes. Both the slits and the diffraction pattern are visible to the unaided eye.*

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. Feynman, in introducing an electron diffraction thought experiment.[1]

An experiment, essentially equivalent to the one so vividly described by Feynman, uses photons which are allowed, one at a time, to pass through a double slit and impinge on a phototube where their energy is given to single electrons.[2] A double-slit interference pattern is gradually built up when the photon impact points are recorded, but if the photons are tagged to determine which slit each one passed through, the pattern that is built up no longer shows the rapid spatial oscillation characteristic of two-slit interference. In either case, the photoelectric effect occurring at the phototube shows the light to be a "particle."

This article describes a simple method of carrying out this experiment in a beginning physics laboratory. Both wave and particle aspects are observed simultaneously and directly in a pattern made by single photons that are interfering with themselves.

The experiment exploits a few of the capabilities of a remarkable photon detector—the eye. Of particular importance is its memory or integration time of $\sim 1/30$ sec, its low noise, and the large number of detecting elements (rods and cones) available. The ability of the dark adapted eye to detect signals at the several-photon level is *not* needed; thousands will be available per integration time.

The basic idea of the experiment is this: The eye can easily recognize an interference pattern with a flux of, say, $10^5$ photons per 1/30 sec. Each photon exists for $\sim 10^{-9}$ sec, so the average number present at any instant is about $10^5 \times 30 \times 10^{-9} = 3 \times 10^{-3}$. If the *entire* pattern is then allowed to fall on the face of a photomultiplier, the individual pulses can be seen. If the photomultiplier gain as well as the quantum efficiency is known, the average number of photons present can also be calculated from the anode current. With the entire pattern on the face, tube noise is generally no problem even though it would usually be in any attempt to trace out the detailed structure of the interference pattern at that light level.[3]

## PREPARATION

Preceding labs in the course have included a simple geometrical optics experiment, a diffraction and interference experiment (light as waves), and a measurement of Planck's constant using a photocell (light as particles).[4] Each lab builds on the techniques or results of the preceding ones, and in each one an attempt is made to derive a result with a minimum of black boxes and a minimum of assumptions. For instance, in the interference experiment, before switching to a grating, a crude measurement of the wavelength of the mercury green line is made using double slits which are large enough ($\sim 0.1$ mm wide) to be measured with a low-power traveling microscope. Thus the students measure the wavelength of light in terms, ultimately, of a millimeter scale visible to the unaided eye. The measured spectral lines from the same mercury lamp (selected by colored filters) are then used in conjunction with a photocell, a reference voltage, and a current meter in the measurement of Planck's constant. With the wave and particle properties separately demonstrated, only one "apparatus" lab is needed before the students are ready for the single-photon interference experiment—one in which the photomultiplier is studied and its gain measured.

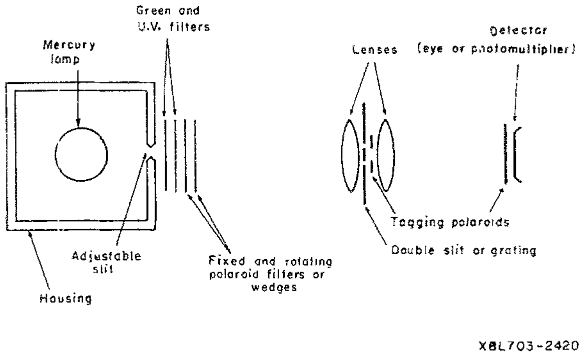


FIG. 1. Schematic diagram of apparatus.

## APPARATUS

The equipment is shown schematically in Fig. 1. It consists of a low-pressure ($\sim 1$ cm Hg) mercury arc lamp, green, ultraviolet, and polaroid filters, two thin lenses, a double-slit pattern from the Cornell Slitfilm demonstrator,[5] a photomultipler,[6] and an oscilloscope.[7] An adjustable slit in the lamp housing together with the ultraviolet blocking and green transmitting filters limits the light to a beam composed predominantly of the 5461-Å line whose intensity is further adjusted with a pair of crossed Polaroid filters or neutral density wedges. A thin lens immediately ahead of the double slit can be used to make the incident light parallel, and one immediately after it is used to focus the interference pattern on the photomultiplier face. Either a grating[8] or a pair of slits can be used. The usual advantages of a grating, improved intensity and resolution, are of course not so important here, and double slits are conceptually simpler. A convenient choice is the pair on the Cornell Slitfilm demonstrator having a 0.35-mm separation but with the slit length masked down to 5 mm.

## PROCEDURE

The execution of the experiment is straightforward. The equipment is set up to give the desired interference pattern using a moderate light intensity with the pattern brought to a focus on the photomultipler face. The intensity is reduced until a sufficiently low count rate or anode current is reached, and the light is blocked momentarily at the slits to demonstrate that the signal is due to the interference pattern. Often at this point the students will discover and have to eliminate some source of extraneous light. Then, with the photomultiplier removed, they should be able easily to see the patterns with both of the slits open and with either one closed. If a grating is used, its larger angular deviation makes it possible to view, simultaneously, part of the pattern with the multiplier and part with the eye.[8] The photon counting rate can be measured without a scaler by triggering the oscilloscope randomly several times per second (for instance on larger-than-average input pulses) and counting pulses per sweep on a specific part of the sweep. Typically they might look at a 10-$\mu$sec interval on 50 sweeps and see a total of 90 pulses. To subtract pulses due to tube noise they look at 50 more sweeps with the slits blocked; 30 might be an average noise count. Thus, there are on the average $90-30=60$ pulses per 50 sweeps due to light from the slits, or 60 pulses/$(50\times 10\ \mu\text{sec})=1.2\times 10^5$ pulses/sec. Since the quantum efficiency $\epsilon$ is about 0.1, each detected photoelectron corresponds to about 10 times as many incident photons. Therefore the number of incident photons per second in this example would be $1.2\times 10^6$/sec.

## AVERAGE NUMBER OF PHOTONS PRESENT

The experiment measures the number of photoelectrons per second, $N_e$. The average number of photons present at any given instant is $n=N_e\tau/\epsilon$, where $\tau$ is the average lifetime of the photons and $\epsilon$ is the quantum efficiency of the photomultiplier. From a particle point of view, $\tau=d/c$, where $d$ is the distance between the source and the detector. While this does give the lifetime of a photon in the radiation field, not all of these photons will be able to interfere with each other if the length of the wavetrain, $d_{\text{coh}}$, is less than $d$. The lifetime corresponding to $d_{\text{coh}}$, $\tau_{\text{coh}}=d_{\text{coh}}/c$ is that of the radiating excited state. It can be found by measuring the coherence length of the light in an unequal-arm Michelson interferometer and is $\sim$(5–6 cm/$3\times 10^{10}$ cm sec$^{-1}$)$\cong 2\times 10^{-10}$ sec.[9] Since this is much less than $\tau$, we can say that the complete wave train is created in about 0.2 nsec, travels through space for about 1 to 2 nsec, and is then absorbed. (The measurement with the Michelson interferometer can take from 1 to 6 h, depending on the skill of the students in aligning the mirrors. It forms part of an optional experiment during the following quarter. It might be desirable to have an interferometer already set up for demonstration purposes in this lab. Then a few minutes should suffice.) The restriction of $n$ to be the average number of photons present in the coherence region further reduces its value by a factor of about 5 from the rough estimate of $3\times 10^{-3}$ given in the introduction. If, on the other hand, the source-detector distance $d$ is less than $d_{\text{coh}}$, then $\tau=d/c$ is the appropriate time to use in finding the average number of photons in the radiation field capable of interfering with each other. The number of photons present is still $N_e\tau_{\text{coh}}/\epsilon$, but some of them are now in the localized Coulomb fields of excited atoms that have not yet radiated. In any event, to convince the more skeptical students that the photons do not, in some unexplained way, manage to interfere with other photons ahead of or behind them, that this almost unbelievable law does not have an escape clause somewhere in the fine print, it really helps to have *both* $\tau$ and $\tau_{\text{coh}}$ short enough so that even if the longer time were used, a value of $n\ll 1$ would result.

The quantum efficiency $\epsilon$ is the one quantity that must be taken from the manufacturer's specifications since an absolute measurement is not practical with the time and equipment available. However, since the probability of two photons being present in the interference pattern at the same time is less than $10^{-2}$, it would take more than a hundredfold error in the specified value to invalidate the experiment.

The quantum efficiency can be measured relative to a secondary standard to within a factor of about two without too much trouble, although an additional lab period would probably be required. For instance, a small NaI(Tl) scintillator (efficiency of one photon per 25 eV energy deposition)[10] and a gamma source in the 10-keV region can serve as such a standard. The signal pulse height will be proportional to the product of the light collection efficiency (which should be close to 100%), the quantum efficiency, and the tube gain.

## TAGGING THE PHOTONS

In Feynman's thought experiment an attempt was made to determine which of two slits each electron passed through on its way to the detector.

The space immediately downstream from the slits was illuminated, and photons scattered from the electrons were detected as flashes of light coming from near one slit or the other, identifying perfectly the slit but destroying the double-slit pattern. Only when he used sufficiently "gentle" (long wavelength) light, was it restored, and by that time the size of the flash had fuzzed out to become equal to the slit spacing. Up to that point, the photons carried sufficient momentum to scatter the electrons through an angle greater than that between interference maxima; after it their wavelength had become too long to resolve the slits.

The equivalent test in this experiment would involve bouncing low-energy electrons ($\lambda \sim 0.01$ mm, kinetic energy $\sim 10^{-8}$ eV!) from the photon and measuring their recoil directions. Since there would be certain experimental difficulties in doing this, we use another source of electrons in tagging our photons—three pieces of Polaroid. One is placed behind each slit, the first with its transmission direction parallel to, and the second perpendicular to the slit direction. As this is done the double slit modulation vanishes, and two partially separated single-slit patterns appear. When the third piece of Polaroid is placed immediately in front of the eye and rotated, one pattern and then the other vanishes at 90° intervals. If crossed Polaroids are also used at the source to adjust its intensity, the last of the two should be set at 45° to the slit direction to provide equal amplitudes for the two slit Polaroids.[11]

The setup is best made by removing the Slitfilm demonstrator from its protective glass cover and using thin pieces of Polaroid (0.25 mm or thinner) permanently mounted directly on the film to avoid parallax and alignment problems. The upper third of the slits is covered with two pieces having perpendicular transmission directions, the middle third is left clear, and the bottom third is covered with two pieces having parallel transmission directions. The latter is used to show that it is not the material or possible edge imperfections that destroy the double-slit interference. A small mask is then used to select the desired combination. Some care indeed must be taken in cutting the Polaroid to prevent edge imperfections from destroying the interference. An easy way to prepare smooth edges is to place the Polaroid under a single-edged razor blade which is then tapped lightly with a hammer.

Only several maxima are observed in this experiment due to the substantial width of the slits (0.07 mm). However a discussion of the idealized case with two very narrow slits (width$\ll\lambda$ photon) may be illuminating. The maxima then repeat many times and with essentially equal intensities. When the two pieces of Polaroid are placed behind the slits, we do not detect single recoil electrons in direct analogy with the electron-interference experiment but rather the coherent radiation of many electrons in the Polaroid. This, when added to the incident radiation, cancels one component, leaving a wave with polarization parallel to $\hat{x}$ in one case and $\hat{y}$ in the other. Since the intensity is proportional to $|\mathbf{E}_1+\mathbf{E}_2|^2=|E_1\hat{x}+E_2\hat{y}|^2=E_1^2+2E_1E_2\cos 90°+E_2^2$, the interference term drops out and the resultant time-averaged intensities are uniform. With the analyzing Polaroid aligned parallel to $\hat{x}$ or $\hat{y}$, the slit traversed by the photon can now be determined. With a piece of calcite or a Nicol prism similarly aligned, the determination can be made photon by photon for both slits simultaneously. In neither case will a double slit interference pattern be seen.

At this point an interesting opportunity presents itself. The waves from each slit are present, polarized differently to be sure, but not otherwise mutilated. Suppose we modify the polarization somehow. Can we get around the uncertainty principle difficulties of the electron-interference experiment and produce double-slit interference with photons that have been tagged as passing through one specific slit? At the source we had a pair of Polaroids to adjust the intensity. Placing the second of these at 45°–225° now serves not only to provide a wave with equal amplitudes at the $\hat{x}$ and $\hat{y}$ slit Polaroids, but also with a constant phase difference at them (zero, for instance, for equal path lengths between the source and slits). As we move along the plane of the detector, the path difference from the two slits changes by $\lambda$ and the phase difference between $E_x$ and $E_y$ changes by $2\pi$ in a spacing equal to the former interfringe distance. This produces a pattern that changes from linear polarization at 45°–225° through elliptical, right-hand circular, and then elliptical to linear polarization at 135°–315°. The cycle is completed through elliptical, left-hand circular, and elliptical back to 45°–225° linear polarization. Thus, the double-slit interference pattern can be restored by placing either a circular analyzer or a tilted (45°–225° or 135°–315°) linear analyzer in front of the detector. But light coming from such an analyzer will come with exactly equal probability from either slit. We have utterly destroyed any polarization information that would identify the specific slit the photon passed through!

It's a unique experience, sitting there, watching the pattern, one photon coming in at a time, knowing that you are, at that moment, probably as close to understanding as you will ever come—so close and yet so very far.

## ACKNOWLEDGMENTS

I would like to thank Forrest Mozer who, while revising the experiments in the beginning laboratory, realized the importance to the student of being able to see the individual single-photoelectron pulses and designed the equipment to accomplish it. His continued interest in the further development of this experiment is greatly appreciated.

[1] R. Feynman, R. Leighton, and M. Sands, *The Feynman Lectures on Physics* (Addison–Wesley, Reading, Mass., 1963), Vol. 1, p. 37-2.

[2] The first experiment that showed diffraction patterns remained unchanged at low light intensities was by G. I. Taylor [Proc. Cambridge Phil. Soc. **15**, 114 (1909)]:

> ...Photographs were taken of the shadow of a needle, the source of light being a narrow slit placed in front of a gas flame. The intensity of the light was reduced by means of smoked glass screens.... The longest time was 2000 hours or about three months. In no case was there any diminution in the sharpness of the pattern....

In that longest exposure the photon density was less than $10^{-5}$ photons/cm$^3$!

[3] Such an experiment is described in R. H. Biser, Amer. J. Phys. **31**, 29 (1963). He uses a cooled photomultiplier and more elaborate equipment. A PSSC film by John King showing the scanning of an interference pattern at low light levels is reviewed in M. Correll, Amer. J. Phys. **30**, 772 (1962).

[4] These labs are described in Forrest Mozer, Physics 4D Laboratory Manual (unpublished). Much of the spirit of this course, in which beginning students are brought in contact with significant experiments and modern equipment, comes from A. Portis, *Laboratory Physics, Berkeley Physics Laboratory* (McGraw–Hill, New York, 1966).

[5] The Cornell Interference and Diffraction Slitfilm Demonstrator is a slide containing various single and multiple slits. It is available from the National Press, Palo Alto, Calif. See also Seville Chapman and Harold Meese, Amer. J. Phys. **25**, 135 (1957).

[6] An over-all gain of $\sim 10^7$ $(g=q/e\approx VC_{\text{input}}/e)$ would be necessary to see single-photoelectron pulses directly with our laboratory oscilloscopes which have a sensitivity of 0.1 V/cm and an input capacity of 47 pF. We use 10-stage photomultipliers (surplus RCA 6655's) having a gain of $\sim 10^6$ with a base designed by Forrest Mozer that uses an integrated-circuit amplifier. It has an effective input capacity of 0.5 pF and an output capable of driving the scope.

[7] A number of companies (e.g., Telequipment, Pasco Scientific, and Heath) now sell inexpensive, triggerable oscilloscopes with bandwidths in excess of 1 MHz.

[8] We use a 527-line/mm replica transmission grating available from the Edmund Scientific Co., Barrington, N.J.

[9] A superb discussion of coherence, interference, and the uncertainty principle can be found in F. Crawford, *Berkeley Physics Course* (McGraw–Hill, New York, 1968), Vol. 3, pp. 427–436, 453–490.

[10] Robert Swank, Ann. Rev. Nuc. Sci. **4**, 114 (1954), G. T. Wright, Proc. Phys. Soc. (London) **B68**, 929 (1955).

[11] Whether neutral density filters or crossed Polaroids are used to attenuate the source intensity, the light from either to the slits must also be (and is) coherent in phase as well as equal in amplitude. The individual Polaroid or filter atoms constitute a secondary source of light that is driven by the primary source and reradiates, coherently, part of the incident light. The requirement of coherence at the double slits puts a limitation on the width of the primary source itself since the population of excited atoms and the phase of their radiation changes randomly in times comparable to $\tau_{\text{coh}}$. An illuminating discussion of this point is found in F. Crawford, Ref. 9, pp. 470–473.