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SINGLE-PHOTON, DOUBLE-SLIT INTERFERENCE--A DEMONSTRATION*

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ABSTRACT

Apparatus is described which produces an interference pattern using only one photon at a time. It can be used in a lighted room--no significant dark adaption is needed to see the pattern, even at the one-photon level. The number of photons per second producing the pattern is measured in the same apparatus with a photomultiplier.

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A previous article described an experiment for a beginning physics laboratory in which the wave-particle duality was demonstrated by the direct observation of an interference pattern made by single photons interfering with themselves.[1] The pattern was first viewed in a dark room. A photomultiplier was then used to detect the discrete, photon-induced pulses and to measure their rate. Besides the dark room and the time required (two to three hours), a moderate familiarity with oscilloscopes, photomultipliers, and similar hardware was needed. The apparatus described here makes this unnecessary and can be used for demonstrations in non-laboratory, beginning courses.

The basic idea of the demonstration remains unchanged: 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 <u>entire</u> pattern is then allowed to fall on the face of a photomultiplier, the individual pulses can be seen. With the entire pattern on the tube face, tube noise is much less of a problem than it is when attempting to trace out the detailed structure of the interference pattern.

There is however, an additional challenge to be met here: The apparatus must be easy to use and foolproof (unless you have access to a rather large supply of phototubes) and yet the students should be able to control the essential parts of the experiment, <u>look</u> at the double slits directly, <u>see</u> the interference pattern itself, and, if there is time, take the crucial measurements to show that only one photon at a time is present. Ideally, there should be some doubt in the students' minds, before the experiment is completed, that it <u>really</u> will turn out that way. Afterwards, hopefully, they may believe there is something very strange going on; that they have caught and seen with their own eyes, one aspect of the central mystery of quantum mechanics.

What we do is this: put the phototube in one light-tight enclosure and the light source and double-slit system in another (a Lucite cylinder). The source, slits, and the interference pattern they make are then rotated as a unit, first to point to the observer and then to the phototube. Sliding, light-tight seals made with black felt protect the phototube from room light.

SLIT SIZES

Mechanical considerations make a small source to double-slit distance desirable. To produce the usual double-slit fringes, the angular width of the source as seen from the double-slits must be less than the fringe angular separation:

$$\frac{d_1}{\ell} << \frac{\lambda}{d_2}$$

$$d_1 d_2 << \ell \lambda$$

where d_1 is the width of the source, d_2 is the double slit separation, and ℓ is its distance from the source.[2] The wave length, λ, is fixed so the small value for ℓ (130 mm) requires a somewhat smaller slit separation than used in Ref. 1. Even with narrowest available single-slit pattern (0.044 mm) cut from a Cornell Slitfilm demonstrator[3] as a source-slit, we must go to the pair with $d_2 = 0.176$ mm for the double-slit. Then

$$0.044 \times 0.176 << 130 \times 5200 \times 10^{-7}$$

$$0.0077 << 0.0676.$$

THE EQUIPMENT

Figure 1 shows a photograph of the apparatus and Fig. 2 a cross section diagram. The light source,[4] green filter, and source-slit are mounted on the side of a Lucite cylinder 15 cm in diameter. On the opposite side are mounted double slits, a second, white light for direct illumination of the slits, and a spring-return, push-button switch to control the second light. Except at the double slits, the inside of the cylinder is painted black and the outside is covered with black plastic tape. The rubber face-piece from an oscilloscope viewing hood[5] provides enough light shielding so the pattern can be easily seen.

In normal operation the cylinder is rotated so the double-slits appear in the viewing port. Lifting the lever on the left side of the hood (see Fig. 1) depresses the push-button switch and illuminates the slits from close behind with the second light. With the aid of a low power magnifier, the double slits can be clearly resolved. Then with the direct illumination push button off, and the source-slit bulb on, at least three maxima of the interference pattern can be seen with no need to wait for dark adaptation. A slight rotation of the cylinder may be necessary to align the pattern with the pupil of the eye. Next, the cylinder is rotated to align the double slits with the lens and photomultiplier (and to move the direct illumination push button safely out of reach!). The black tape, paint, and felt now seal room light from the slit-photomultiplier system.

Figure 3 shows details of the photomultiplier, shield, and base system.[5] The requirements on gain G, (10^7 - 10^8), quantum efficiency (10% - 20%), and noise ($< 10^4$ sec^{-1} at the one-photon level) are easily met by the 56AVP used here and by many other tube types as well. With gains of this order, many common, inexpensive oscilloscopes[7] will be adequate if the photomultiplier signal is stretched to a length of about 1 μsec. An easy way to do this is to connect the photomultiplier anode output to the scope input with a short length of coax cable terminated with a resistance of about 5 KΩ. The peak signal will then be

$$V_{peak} = \frac{Q}{C} = \frac{eG}{C_{pm} + C_{base} + C_{cable} + C_{scope}} \approx \frac{1.6 \times 10^{-19} \times 10^{8}}{10^{-10}} \approx .1\text{V}$$

and the decay time will be

$$\tau = RC \approx 5 \times 10^{3} \times 10^{-10} \text{ sec} = .5\ \mu\text{sec}.$$

THE TEST

When the interference pattern is rotated to fall on the photocathode a large increase in counting rate should be seen. The heart of the experiment involves demonstrating that we are detecting one quantized packet of energy--one photon-- and only one photon at a time. (Hopefully, the student already understands something about interference of waves, by having seen demonstrations with ripple tanks, stereo loudspeakers, light waves or whatever.)

Let's start with a sweep speed where motion can be directly seen--say 100 cm/sec. The pulses, coming in at perhaps 10^5/sec, form an apparently continuous fuzz of "grass" on the scope trace. As the speed is increased step-by-step, first structure, then individual pulses and baseline between the pulses come into view. The baseline carries an important message: Energy is being transferred to the tube in discrete packets.

Next we measure the rate. If no scaler is available, the rate can be measured by triggering the scope randomly (for instance, by touching the leads from a 30V dry cell to the external trigger input) and counting the number of pulses per sweep of amplitude greater than some fixed minimum. Are there pulses still being missed? Raise the photomultiplier voltage. Perhaps there will be an endlessly smaller succession of pulses coming into view as we look with ever higher voltage. No! Here in Table I are the results of a typical data-taking run. The scope gain was set at 0.1 V/cm, and the sweep at 10 μsec/cm for the noise counts or 1 μsec/cm for the light-on counts. Pulses larger than 1 cm were counted.

The noise rate is about 10^3/sec and is completely negligible. As the voltage is increased the light-on counting rate first increases, then reaches a plateau. At the higher voltages, most of the pulses go off the screen when the oscilloscope is set for 0.1 V/cm; there are essentially no small pulses. We are seeing, through the enormous multiplying power of 14 dynodes, the quantization resulting as photons arrive at the photocathode and eject single electrons. Thus we have observed two aspects of quantization--discrete pulses and a minimum pulse size. Since there is an accelerating field at the photocathode, we are not able to measure, with this apparatus, the discrete *energy*, $E = h\nu$, given each electron.

Finally, the single photoelectron rate is

$$r = (82 + 91 + 92 + 82)/(4 \times 250\ \mu\text{sec}) = 3.5 \times 10^5/\text{sec}$$

and the average number of photons in the space between the source and the detector (excluding those stopped by the slits) is

$$N = \frac{1}{\epsilon}\ r\ \frac{L}{c} = \frac{(3.5 \times 10^5/\text{sec}) \times (20\text{cm})}{(0.20) \times (3 \times 10^{10}\ \text{cm/sec})} = 1.2 \times 10^{-3}$$

where ϵ is the phototube quantum efficiency and L is the source-detector distance. I haven't thought of a good way to measure ϵ in a demonstration at this level. In any event, even an error in the specifications by a factor of 100 would leave N much less than 1. N is also equal to the fraction of the time that a second photon will be present when one is already in transit. The probability that another will be within a coherence length of the first and coneivably capable of interfering with it is even smaller due to the short coherence length of the light.[8]

Figure 4 shows a photograph of the diffraction pattern taken with a view camera substituted for the eye. The lens (an f/6.8 Goerz Dagor) was 22 cm from the slits and was focussed at infinity. The film (Royal-X Pan, ASA 1250) was 15 cm from the lens and was exposed for six minutes at an average intensity corresponding to 0.006 photons in flight at any given time.

Would you like to get an idea of what the pattern looks like without building the apparatus? You will need darkness. Take a small desk lamp with a 60 watt bulb. Cover it with a sheet of dark green cellophane. Place the photograph 15 cm from the bulb and 15 cm from your eyes. Close one eye. Imagine a source in the darkness deep behind the page.

Now look.

ACKNOWLEDGEMENTS

I would like to thank Richard Muller for his interest in this demonstration and for suggesting the use of an oscilloscope hood to provide both light shielding and alignment of the eye with the very narrow interference pattern.

REFERENCES

* Work done under the auspices of the U.S. Atomic Energy Commission.

1. S. Parker, Amer. J. Phys. 39, 420 (1971).

2. An equivalent way of deriving this relation is given in F. Crawford, Berkeley Physics Course (McGraw-Hill, New York, 1968) Vol. III, pp. 453-473. He starts from the requirement that the two slits be illuminated by a coherent source, that is, that there be a constant phase relation between the waves reaching each slit. This requires that the path difference from any source point to the two slits must vary by much less than λ as the position of that point is varied over the source, since otherwise the phase difference would change as the population of radiating atoms changes.

3. 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, CA. See also, S. Chapman and H. Meese, Amer. J. Phys. 25, 135 (1957).

4. The light source was an ordinary pilot light, a GE 1815, 12 V, 0.2 A bulb, covered with a piece of dark green cellophane which transmitted about 6% of the visible light.

5. The rubber part of a Tektronix oscilloscope hood, number 016-0153-00 was used.

6. Any number of systems will do. The one used here is described in S. Parker, W. Oliver, and C. Rey "A Photomultiplier Base and Shield System," Lawrence Radiation Laboratory Report, UCRL-18031, Jan. 11, 1968 (unpublished).

7. Inexpensive, triggerable oscilloscopes with bandwidths in excess of 1 MHz are now available from a number of companies including Heath, Pasco Scientific, and Telequipment.

8. This point is discussed more fully in Ref. 1 and in F. Crawford, Berkeley Physics Course (McGraw-Hill, New York, 1968), Vol. 3, pp. 427-430.

Table I. Data

HV (in kV)	Light off (noise) (counts/250 cm = 2.5 ms)	Light on (counts/250 cm = 0.25 ms)
2.0	0	3
2.1	1	36
2.2	1	82
2.3	1	91
2.4	3	92
2.5	2	82

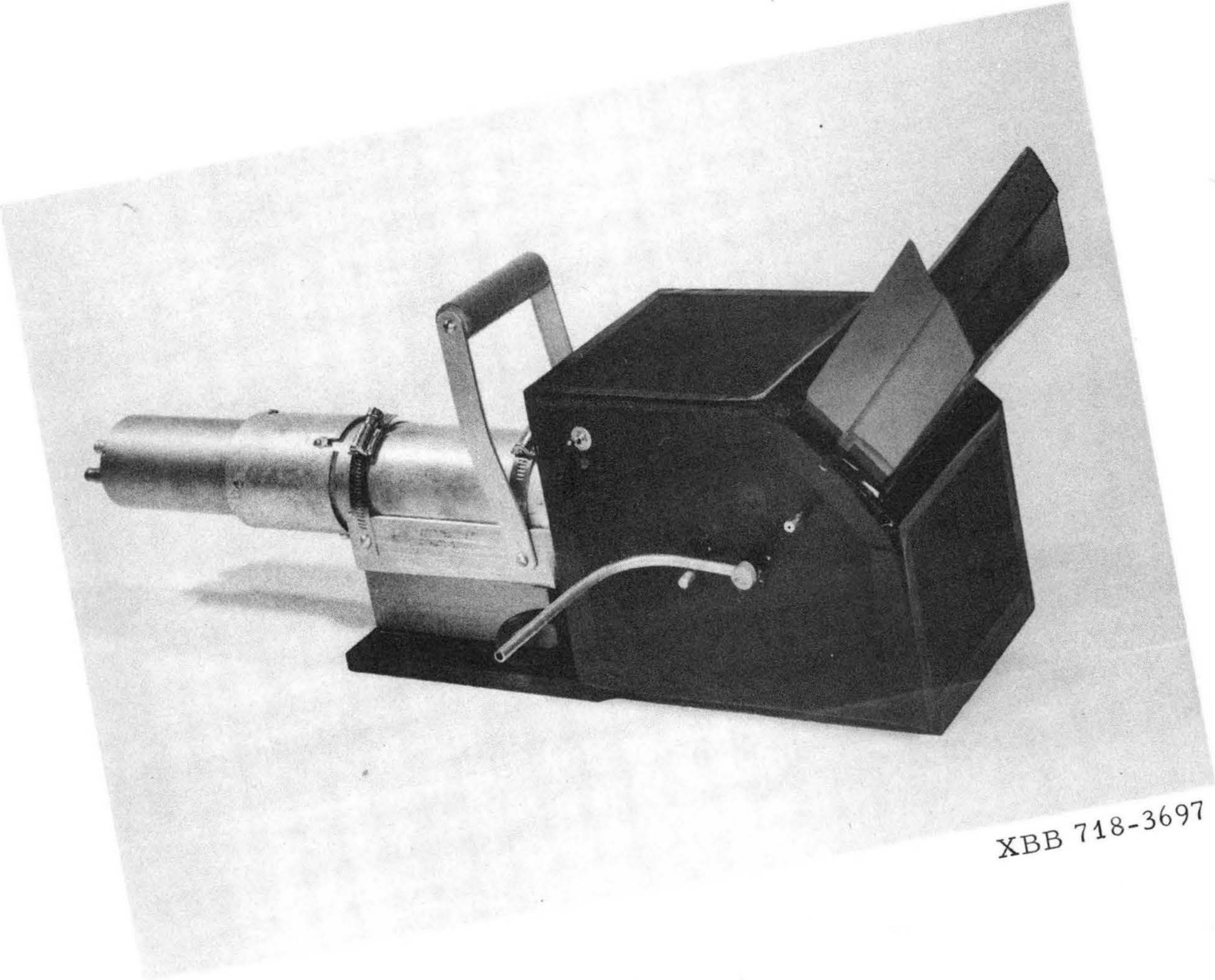
FIGURE CAPTIONS

Fig. 1. Photograph of the apparatus. The handle position shown aligns the interference pattern with the phototube. The stops limit its motion to prevent the wiring from being wound up around the axle. The short lever near the base of the viewing hood operates the direct illumination push-button switch.

Fig. 2. Cross-section view of the apparatus.

Fig. 3. Exploded cross-section view of the photomultiplier shield and base assembly.

Fig. 4. The diffraction pattern, taken with an average photon intensity corresponding to 0.006 photons in flight at any given time. The fringe separation both in this figure and on the original negative is 0.5 mm.



XBB 718-3697

Fig. 1

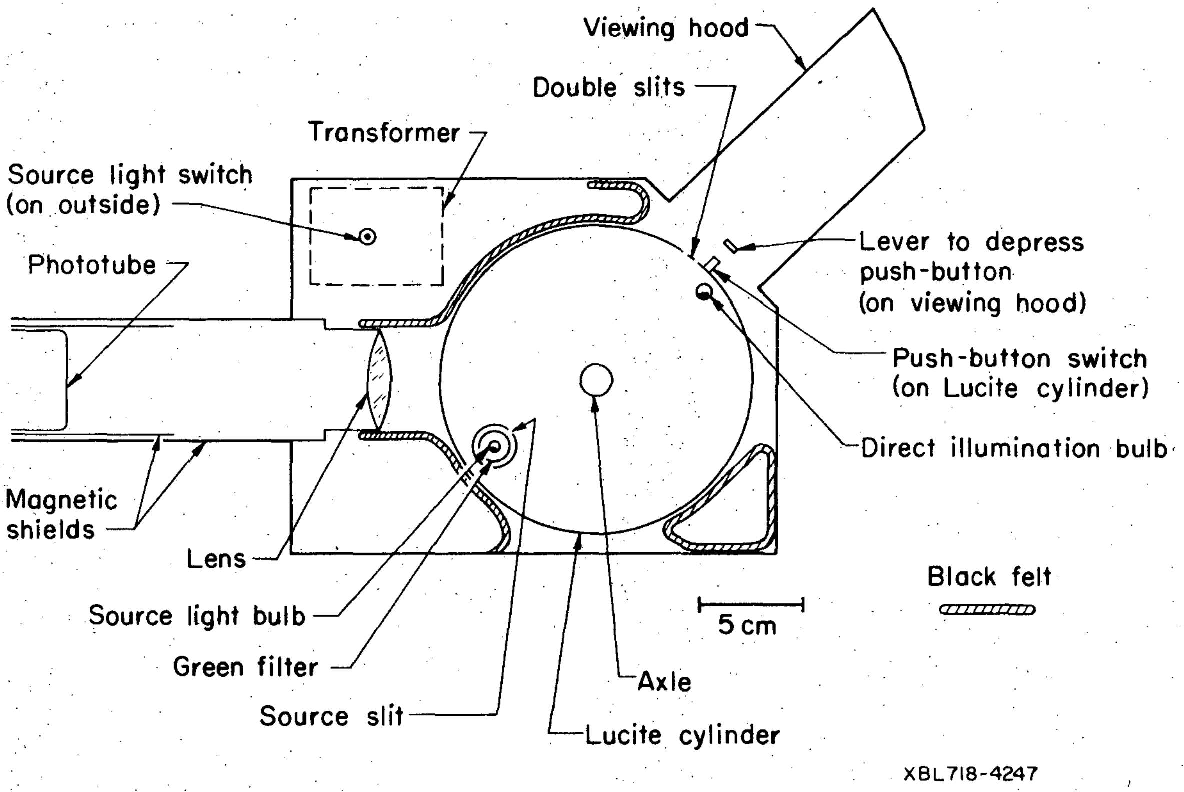
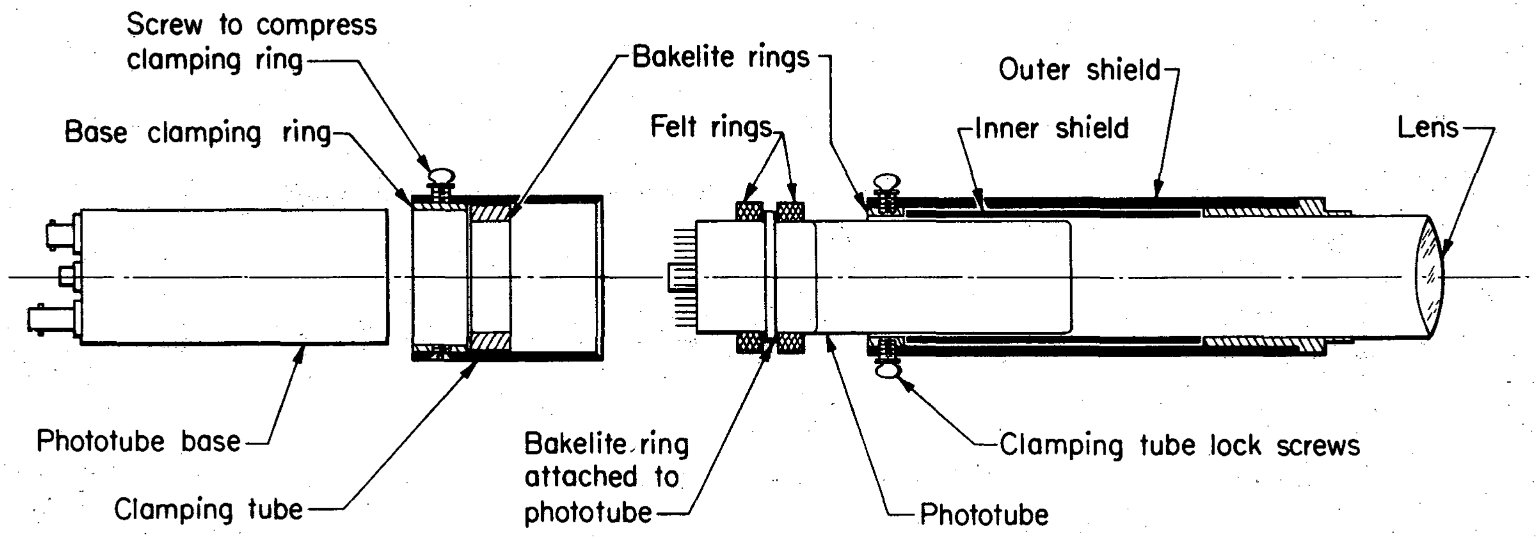

Viewing hood
Double slits
Transformer
Source light switch (on outside)
Phototube
Lever to depress push-button (on viewing hood)
Push-button switch (on Lucite cylinder)
Direct illumination bulb
Magnetic shields
Lens
Source light bulb
Green filter
Source slit
Axle
Lucite cylinder
5 cm
Black felt
XBL718-4247

Fig. 2



XBL 718-4246

Fig. 3

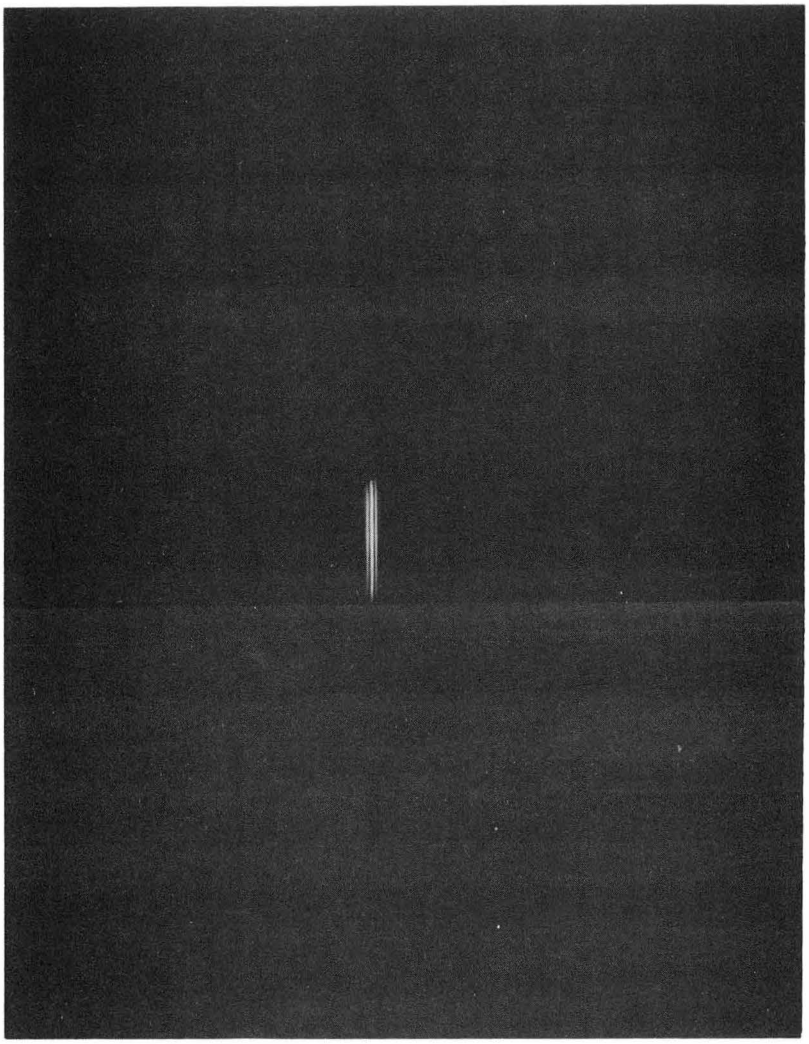


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Fig. 4

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