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Todorka Lulcheva Dimitrova
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The wave-particle duality of light: A demonstration experiment

T. L. Dimitrova
University of Plovdiv "Paissi Hilendarski," Tsar Assen Street 24, 4000 Plovdiv, Bulgaria

A. Weis[a)]
Département de Physique, Université de Fribourg, Chemin du Musée 3, 1700 Fribourg, Switzerland

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The wave-particle duality of light plays a fundamental role in introductory courses on quantum mechanics. Traditionally the wave and particle aspects of light are demonstrated in separate experiments which makes it difficult for students to understand their complementary nature. We present an experiment using a single apparatus that demonstrates the wave aspect, the particle aspect, and most importantly, their coexistence. The apparatus is based on a Mach-Zehnder interferometer in which a light beam is attenuated so that at each instant there is only a single photon in the interferometer. In this way the observation of single photon interference becomes possible. By integrating the single photon events in a storage oscilloscope the evolution toward classical interference fringes can be shown in real time. A second strong laser beam, derived from the same pointer, but slightly displaced, traverses the interferometer at the same time, allowing the simultaneous demonstration of wave aspects. Special features of the setup are low cost, simplicity, didactical power and suitability for presentations in large lecture halls using both multimedia projections and audible signals.
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I. INTRODUCTION

The historical debate on the particle versus wave interpretation of light is well known. The debate between Newton and Huygens seemed definitely settled in favor of the wave nature by the work of Young, Fresnel, Maxwell, Hertz, and others. The discussion was revived by Einstein's interpretation of the photoelectric effect in terms of light being a stream of particles, later called photons. The wave and particle aspects were unified by Bohr and Heisenberg who introduced the concept of complementarity, which was later identified as a distinguishing characteristic of quantum mechanics: contradictory properties of a physical system, here particles and waves, are interpreted as complementary properties, and a complete description of the system is obtained only when considering both properties (duality). Later the wave-particle duality was given a simple interpretation by stating that light propagation is described by a quantum mechanical wave function with the same superposition and interference properties as a classical wave. The particle nature is revealed at the moment of detection when the wave function collapses. Put simply, light behaves as a wave when it propagates and like a particle when it is detected.

First year students can grasp the alternative manifestations of light as either particles or waves, depending on different experimental conditions, but usually have problems understanding the simultaneous existence of both properties. At this point lectures usually discuss a Gedanken experiment, in which we imagine classical two-beam interference with light waves so weak that at each moment there is only a single photon in the apparatus. However, there are no standard demonstrations that illustrate the simultaneous visualization of the wave and particle aspects of light.

Single particle interference experiments have been performed with massive particles such as electrons (for example, Ref. 1), neutrons (for example, Ref. 2), atoms and molecules (Ref. 3 and references therein) up to molecules as large as $C_{60}F_{48}$.[4] Beautiful as these experiments are, they are not suitable for lecture demonstrations of wave-particle duality. This difficulty is often bypassed by presenting simulations. The web site of Physics 2000[5,6] provides an interactive applet which simulates the double slit experiment with single electrons together with a detailed discussion between students and teachers following the Socratic method.

Following earlier recordings of single photon interference by photographic plates[7] and even the unaided eye,[8] the Gedanken experiment we will discuss was realized as a practical demonstration experiment in 1996 using a video camera[9] and in 2003 using a charge coupled device (CCD) camera.[10] In both experiments the interference pattern from a double slit illuminated by a strongly attenuated red laser was recorded on a photon by photon basis. The attenuation was so strong that at each moment only a single photon was in the vicinity of the double slit. Each frame recorded by the camera shows an apparently random distribution of photons, illustrating the particle nature of light. After the integration of a sufficient number of frames, the classical wave interference pattern emerges. The German version of Physics 2000[6] shows a movie of this process recorded by the authors of Ref. 10. In the context of events related to the World Year of Physics (2005) one of us (A.W.) built an improved version of this experiment using light from a green laser pointer and a camera with a higher pixel resolution. Figure 1 shows a series of interference patterns recorded with this device.

The purpose of the work we report here is to propose to a similar, but lower cost experiment which avoids the prohibitively high cost (≈20 000 EUR) of the CCD camera.

II. PEDAGOGICAL IDEA AND METHODOLOGICAL ADVANTAGES

The main aim of the experiment is to give students a convincing demonstration of the dual nature of light. Classical demonstrations of the wave and particle nature of light are usually performed using two distinct experiments and students might get the impression that the two properties of

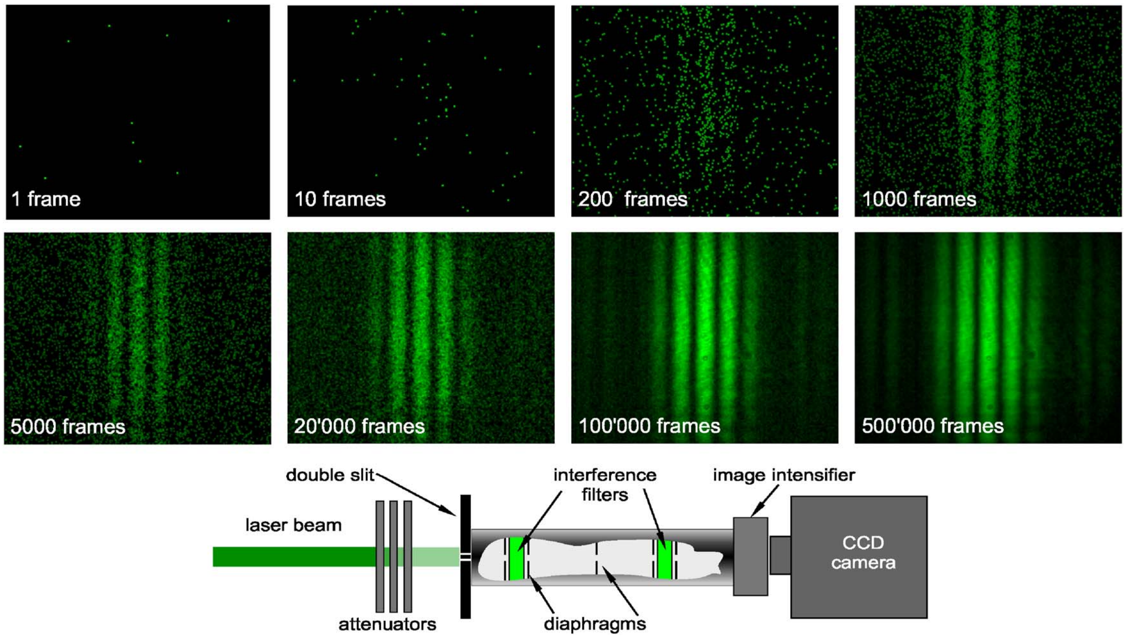

Fig. 1. (Color online) From particles to waves: Detection of light diffracted from a double slit on a photon by photon basis using a single-photon imaging CCD camera. Although single frames show an apparently random distribution of photon impact points, their integration reveals the classical fringe pattern.

light (waves and particles) are mutually exclusive because they appear independently in different experiments. To eliminate this conceptual difficulty we have designed an apparatus in which the particle and wave aspects can first be demonstrated individually. Then the same apparatus is used to visualize the real-time evolution of individual quantum events to a classical wave pattern. The use of the same light source and the same interferometer is important to convince students that we can investigate the two aspects of light with the same apparatus.

Two-beam interference phenomena are often explained on the basis of Young's double slit experiment by displaying the well known interference pattern on a distant screen. Although this example is well suited for a theoretical discussion and most easily realized using a laser pointer and a double slit, it is not practical for advanced demonstration experiments because it does not allow the variation of system parameters in a simple way. In the present experiment we have chosen a Mach-Zehnder interferometer in which a large spatial separation of the two interfering beams can be easily realized, permitting several manipulations, such as the adjustment of the path length difference and the relative angle of the interfering beams, and, most importantly, the easy blocking of one of the two beams. The macroscopic dimensions of the Mach-Zehnder interferometer allow the observer to see all components from the light source via the generation and recombination of the interfering beams up to their detection.

A green laser pointer was chosen as the light source because it has a sufficiently long coherence length for the easy alignment of the interferometer. The intensity of the green beam and its wavelength near the vicinity of the eye's maximum sensitivity ensure that even expanded interference patterns are easily visible in a large auditorium.

Our main design criterion was to have the apparatus as simple and pedagogical as possible while also offering the flexibility to vary certain parameters to illustrate several aspects of the phenomena. The equipment is designed for demonstrations in a large auditorium. The interferometer is mounted on an aluminum plate tilted by 45°, so that all components can be easily seen. If necessary, a webcam can be used to project a close-up of the interferometer table. As mentioned, the expanded fringe pattern using the full laser intensity can easily be seen from a distance without additional tools. Individual photon events can be seen as pulses on an oscilloscope, or heard as clicks using audio equipment. All relevant electronic signals (photomultiplier pulses and photodiode signals) can easily be projected using equipment such as a digital oscilloscope equipped with a video port or a USB-based oscilloscope. Attention was paid to obtain stable pictures and good visibility of all the components and projected signals. Last but not least, we have made an effort to reduce component cost as much as possible, and to give the apparatus a pleasant look.

III. EXPERIMENTAL SETUP

The scheme of the experimental apparatus is shown in Fig. 2 and a photo of its main components in Fig. 3. The light source is a 5 mW green ($\lambda = 537$ nm) laser pointer. The batteries in the laser pointer were replaced by electrical contacts so that the laser could be driven by an external power supply. We found that the spectral width of the laser radiation and hence its coherence length depends on the operating voltage and a randomly chosen pointer has its own optimal voltage for the highest fringe contrast. Once set correctly and after a warm-up time of several minutes this voltage gives reproducible results on daily basis.

The standard Mach-Zehnder interferometer has two beam splitters and two mirrors (all 1 in. optics) arranged in a 18×18 cm^2 square (see Figs. 2 and 3). One of the mirrors is mounted on a low-voltage piezotransducer that allows the voltage-controlled variation of the path length difference (≈ 5 V per fringe).

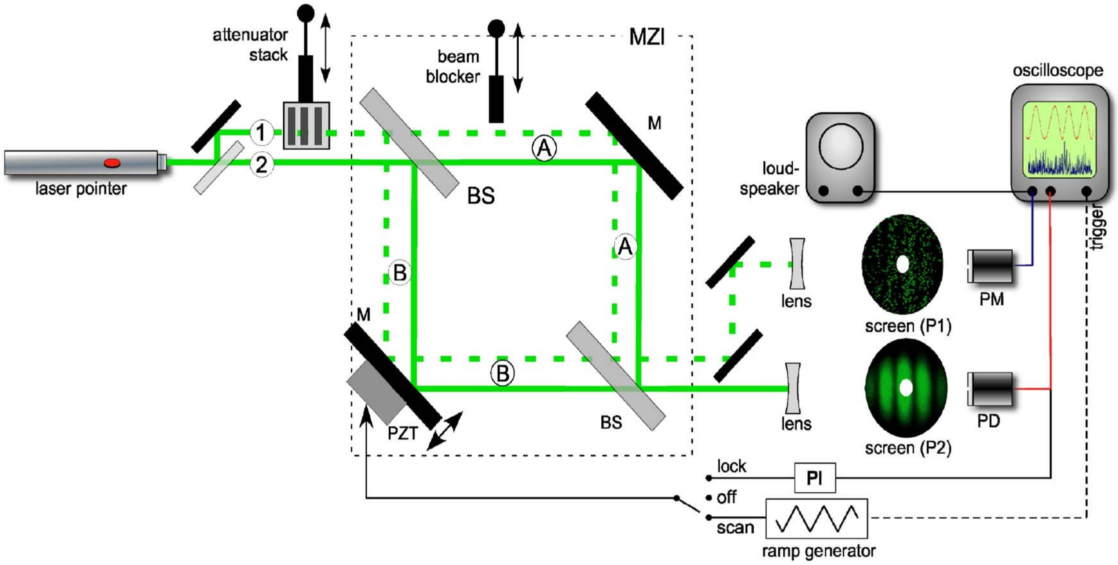

Fig. 2. (Color online) Experimental apparatus for the simultaneous demonstration of the wave and particle nature of light. Both the strong and the attenuated beams are shown here to lie in the plane of the interferometer. In the actual setup (Fig. 3) the beams are in two distinct planes. BS: beam splitter, M: mirror, PM: photomultiplier, PD: photodiode, and PI: feedback amplifier.

Prior to entering the interferometer, the laser beam is split into two beams (beams 1 and 2) of equal intensity; one of the beams can be strongly attenuated by an (insertable) stack of neutral density filters. The two beams are then sent through the interferometer and form two interference patterns on sandblasted aluminum screens. Each screen has a small central aperture behind which a photodiode PD (strong beam) and a photomultiplier PM (weak beam) are placed. The screens are mounted on their corresponding detectors and each unit can be displaced in the transverse direction on a common optical rail. The photomultiplier is equipped with a narrow collimator (C) and interference filters (IF) so that it only detects light at the laser frequency in a small solid angle similar to the one described in Ref. 10. By coincidence the strong green spectral line of Hg is transmitted by the interference filters and care has to be taken when operating the photomultiplier in a room equipped with standard fluorescent lighting. When properly adjusted, the narrow solid angle seen by the photomultiplier collimator permits operation of the system without dimming the room lights.

The photomultiplier (Hamamatsu, model H5784) has an integrated high voltage supply and preamplifier, and requires only a low voltage external power supply and a potentiometer for controlling the high voltage applied to the tube. The output pulses produced by individual photons have a decay time of 20 μs and can be displayed by an oscilloscope or, after discrimination and pulse shaping, rendered acoustically by a loudspeaker.

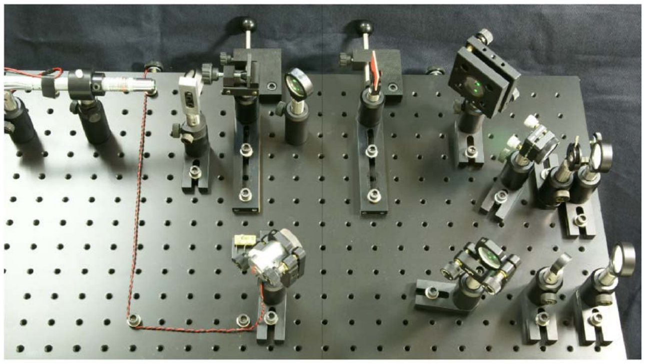

Fig. 3. (Color online) Photograph of the Mach-Zehnder interferometer.

IV. DEMONSTRATIONS OF THE WAVE AND PARTICLE NATURE OF LIGHT AND OF THEIR COMPLEMENTARITY

A. Seeing waves and hearing particles

The wave nature of light can be shown classically as the interference fringe pattern produced by the unattenuated beam 2 on the screen P2 (Fig. 2). Alternatively, we can apply a voltage ramp to the piezotransducer and show the time dependent photodiode signal revealing the sinusoidal intensity modulation (lower trace of Fig. 4). The large spatial separation of the beams easily convinces students that two beams are involved in the experiment. Both beams can be manipulated conveniently including blocking, attenuating, and rotating the polarization, changing the angle between the interfering beams. In the piezotransducer-scanning mode, for example, we easily show that by blocking one arm the interference disappears and the intensity recorded by the photodiode becomes one quarter of the maximum intensity observed in the fringe pattern. Another readily implemented demonstration is the dependence of the fringe spacing on the angle between the interfering beams.

The particle nature of light can be shown by recording the strongly attenuated beam with the photomultiplier while one of the Mach-Zehnder interferometer paths is blocked (see Fig. 2). The photomultiplier pulses can be displayed directly as an oscilloscope trace, or can, after electronic discrimination and pulse shaping, be transmitted to a loudspeaker, so that the detected single photons can be "seen" and "heard." When hearing the photon stream older scientists are often

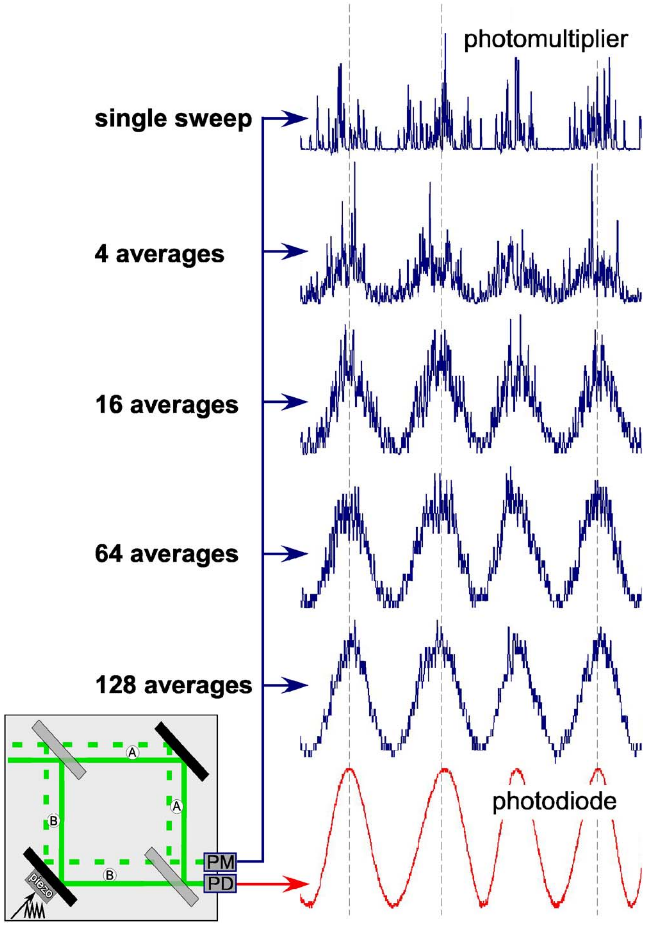

Fig. 4. (Color online) Simultaneous demonstration of the particle and wave aspects of light. The bottom trace shows the intensity distribution measured by the photodiode (wave aspect). The top trace shows the pulsations registered by the photomultiplier. By averaging many traces, the signal from the photomultiplier becomes smoother (the average time increases from top to bottom), and approaches the signal shape from the photodiode.

reminded of the (now less commonly demonstrated) sound from a Geiger counter; a good starting point for an excursion into counting statistics.

B. Hearing single photon interference

Our original idea[11] was to move the two detectors simultaneously through the respective fringe patterns (P1 for the photomultiplier and P2 for the photodiode) which would yield an oscillating current from the photodiode and a periodic oscillation of the click rate from the photomultiplier. When the optical rail carrying the detectors is mounted on the same table as the interferometer, the unavoidable mechanical vibrations associated with the detector motion perturb the interferometer and induce an uncontrolled jitter of the fringe patterns. Thermal drifts of the path length difference yield additional complications. For this reason we have designed an active stabilization of the path length difference and hence of the fringe pattern with respect to the photodiode. An electronic feedback system uses the photodiode signal to control the length of the interferometer arm B using the piezotransducer-mounted mirror (Fig. 2). For this purpose the photodiode is placed at a point in the fringe pattern at which the light intensity is equal to half of its maximum value. The difference between the photodiode signal and a reference voltage (chosen to make the difference null) provides an error signal which, after proportional-integral amplification, is fed to the piezotransducer in a servo-loop. In this way the path length difference can be stabilized and the spatial position of the fringe pattern becomes locked to the photodiode. With the locked fringe pattern a displacement of the photodiode will induce a controllable displacement of both fringe patterns. By keeping the photomultiplier position fixed the photodiode motion moves the pattern P1 across the photomultiplier and the audience can hear a periodic change of the click rate. With a suitably adjusted intensity of the attenuated beam this periodic change manifests itself as a periodic modulation of the sound's pitch. In parallel to the acoustic signals an oscilloscope trace showing the photomultiplier pulses can be displayed.

This experiment is well suited for accompanying a Socratic discussion with students about the nature of light, addressing questions such as the relation between the classical fringe pattern and the periodic modulation of the pulse/click rate, the rectilinear motion of photons, and the dependence/independence of the interfering entities. For this purpose we can use to advantage the Mach-Zehnder interferometer's ability to alter the fringe period. The discussion can lead students to the conclusion that the photon possesses unusual, that is, nonclassical properties.

C. From particles to waves

The experiment in Sec. IV B illustrated the simultaneous appearance of wave and particle aspects which might trigger the students' curiosity about how the two aspects can be combined into a unified picture. We now present an elegant and convincing experiment that shows the evolution from individual quantum events to classical wave interference phenomenon. For this purpose we create a periodic modulation of the light path difference in the two interferometer arms by applying a periodic voltage ramp to the piezotransducer. The signals from the strongly attenuated beam 1 and the full intensity beam 2 are displayed simultaneously as oscilloscope traces. The lower curve in Fig. 4 shows the sinusoidally modulated photodiode signal which represents the interference fringes; the uppermost signal of the figure shows the simultaneously recorded photomultiplier pulses. We see that the density of the photomultiplier pulses is larger in the vicinity of the points of constructive interference, and still displays the quantum nature of the signal. By using the averaging function of the oscilloscope (Tektronix, model TDS20000B), the photomultiplier signal can be integrated as represented by the consecutive traces shown in Fig. 4 (averaging time increasing from top to bottom). For increasing integration times the quantum nature of the individual events is gradually washed out, and we observe a continuous transition to a smooth sinusoidal intensity distribution. After 128 averages the individual quantum events can hardly be distinguished, and the interference pattern becomes identical to the classical pattern detected with the photodiode. In this way we show in real time the transition from a two-beam interference experiment with individual particles to the familiar two-wave interference fringes.

Alternatively, we can produce a similar sequence of pictures as in Fig. 4 by continuously raising the intensity of the weak beam entering the interferometer with a variable attenuator. Due to the finite bandwidth of the recording system,

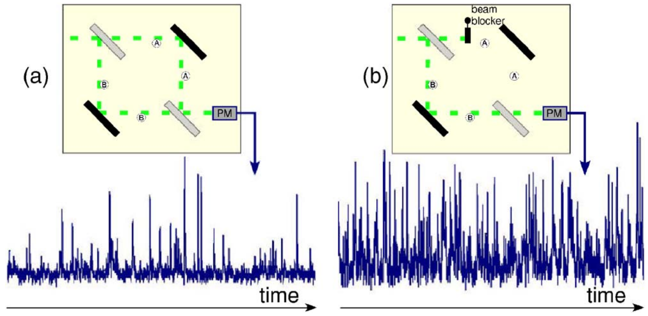

Fig. 5. (Color online) “The photon interferes with itself:” The photomultiplier is set to a minimum in the fringe pattern. (a) Photomultiplier pulses (background) recorded when the photons are offered the alternative of two paths; only a few photons are detected. (b) Photomultiplier pulses when the photons are forced to take a well defined path; the number of registered photons increases.

the pile-up of the individual pulses will converge to a smooth trace. The remaining structure from the individual pulses is a good starting point for discussing the shot noise of the detected signal.

It is also worth mentioning that the photodiode signal is the current produced by a very large number of (conduction band) electrons that were each produced by a single photon via the internal photoelectric effect in the semiconductor forming the photodiode.

We have shown this experiment at conferences, exhibitions, and lectures and have received a unanimous opinion—not only from students—on its unambiguous, convincing and spectacular nature.

D. The photon interferes with itself

This experiment is well suited to accompany a discussion of quantum mechanical “which-way” experiments. The demonstration, whose result is astonishing for students, is realized in the following way. First the fringe pattern is locked to the photodiode as explained in Sec. IV B, and the photomultiplier is moved to a fringe minimum, characterized by a low photon count rate [see Fig. 5(a)] which can also be displayed acoustically. If now path A of beam 1 is blocked inside of the interferometer, it is possible to hear (and see) a distinct increase of the click rate [Fig. 5(b)]. This result demonstrates that if we give each photon the choice of taking either path A or path B, it has a low probability to appear at the detector. In contrast, if we force the photon to follow a specific path by blocking the other path, then its probability to arrive at the detector is much higher. The puzzling fact that a two path alternative for each photon prevents it from reaching the detector, while blocking one of the paths leads to a revival of the clicks, is most intriguing for beginning students. This experiment is well suited for illustrating this remarkable quantum mechanical effect, which can be explained only if we assume that each photon simultaneously takes both paths A and B; that is, each photon, in the phrasing of Dirac, “interferes with itself.”[12]

V. SUMMARY AND OUTLOOK

We have developed a lecture demonstration based on a Mach-Zehnder interferometer which makes possible different presentations related to the wave-particle duality of light. The interferometer operates simultaneously with two interfering beams from a strong laser beam and two interfering beams from the same laser, so weak that at each instant there is only a single photon in the interferometer. The two interference patterns are detected by a photodiode and a photomultiplier, respectively, whose signals can be displayed as oscilloscope traces. In addition, the pulses produced by individual photons in the photomultiplier can be rendered acoustically. Besides demonstrations of the classical two-beam interference in wave optics, the apparatus makes possible the demonstration of different effects associated with the particle nature of light. The most impressive demonstration is an experiment that shows interference fringes in terms of single photon events, which, after integration in a digital storage oscilloscope, can be seen to evolve in real time to the classical interference pattern.

The apparatus discussed in this paper can be used for other demonstrations of quantum effects involving single photons, such as delayed choice experiments. We only mention the possible realization of what is known as the “quantum eraser,”[13] a do-it-yourself version of which has recently been proposed by Hillmer and Kwiat.[14] By implementing orthogonal polarizers in the two paths of the attenuated Mach-Zehnder interferometer beams we can imprint a which-way label to each photon, thereby destroying the interference pattern. A suitably oriented additional polarizer subsequently put in front of the photomultiplier will erase the which-way information and restore the interference phenomenon. In contrast to the strong light demonstration in Ref. 14 our apparatus will demonstrate the quantum nature of the erasing process on a photon by photon basis.

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[a] Electronic mail: antoine.weis@unifr.ch

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Diamond Jar. The diamond jar adds some drama to the process of charging up a Leiden jar. The tinfoil inner and outer coatings of the jar are made up of diamonds with small spaces between their points. As the jar is charged, sparks jump between the points of the diamonds. The device is also called a Spangled Jar. This example is at Case Western Reserve University. (Photograph and Notes by Thomas B. Greenslade, Jr., Kenyon College)