Three Demonstration Experiments on the Wave and Particle Nature of Light

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Kurzfassung
Wir stellen drei Experimente zum Anfassen vor, die den Welle-Teilchen-Dualismus von Licht demonstrieren. Im ersten Experiment werden einzelne Photonen aus einem stark abgeschwächten Laserpointer in einzelne akustische Klicks umgesetzt, um so die Teilchennatur des Lichtes hörbar zu machen. Beim zweiten Experiment handelt es sich um ein gewöhnliches Doppelspaltexperiment zur Verdeutlichung der Wellennatur des Lichtes. Das dritte Experiment zeigt die Synthese dieser beiden Sichtweisen, indem das Doppelspaltexperiment mit einzelnen Photonen durchgeführt wird und mit einer bildverstärkten Kamera in Echtzeit die ankommenden Photonen eines nach dem anderen nachgewiesen werden. Nach einigen Sekunden Mittelungszeit wird in dem zunächst scheinbar unregelmäßigen Muster der Ankunftsorte der Photonen das Beugungsbild sichtbar. Moderne Technik kann somit ein klassisches Gedankenexperiment in ein real existierendes umsetzen, welches sogar für öffentliche Ausstellungen geeignet ist. Außerdem wird eine Version der Experimente für den kleinen Geldbeutel vorgestellt.

Abstract
We describe three hands-on experiments that demonstrate the wave-particle dualism of light. In the first experiment individual photons from a strongly attenuated laser pointer are converted into individual acoustic clicks, thus making the particle nature of light audible. The second experiment is a standard double-slit experiment demonstrating the wave nature of light. The third experiment shows the synthesis of these two views by performing the double-slit experiment with single photons and detecting their interference pattern by registering the photons one by one in real time with an image-intensified CCD camera. After a few seconds of averaging the diffraction pattern emerges out of the seemingly irregular arrival points of individual photons. Modern technology thus can turn a classic gedanken experiment into a real one, suitable for unsupervised public display. A low-budget version of the single-photon diffraction experiment is also presented.

1. Introduction
What is light? This question has been under scientific investigation and debate for several centuries. A comprehensive historical review can be found, e.g., in the introductory chapters of [1] and [2]. Well-known are the 17th century intellectual battles between C. Huygens, a proponent of the wave theory of light, and I. Newton, who favored the interpretation of light in terms of particles. Newton's light particles had very different properties from what we now call photons but were accepted by many scientists until T. Young and later A. Fresnel performed and perfected their diffraction experiments in the early 19th century. The wave theory of light was further strengthened by the successes of Maxwell's theory and Hertz's experiments in the second half of that century.
Planck's results for the blackbody radiation spectrum, presented about 100 years ago, indicated that the walls inside a blackbody absorb and emit light only in discrete quanta of energy. The decisive proof of the particle nature of light came with A. Einstein's theoretical interpretation of the experiments by H. Hertz, by W. Hallwachs, and by P. Lenard on the photoelectric effect: a metal surface illuminated by UV light emits electrons without time lag and with an energy independent of light intensity but proportional to light frequency (when the work function is subtracted).
The resulting confusion due to this dual nature of light was formally resolved by introducing second quantization. Some of the counter-intuitive aspects have been illustrated in recent years by a series of experiments with single photons and single atoms that were made possible by the rapid advances in the field of quantum optics [3, 4]. Still, some (partly philosophical) controversy remains [5]. From an experimentalist's point of view light propagates as a wave and deposits its energy in discrete quanta only, for instance during detection. The square of the amplitude of the electromagnetic wave at a given time and position is proportional to the probability of finding a photon in a small volume centered at this point in space-time (from a theoretical point of

view, there are some subtleties that go beyond the scope of the present context; these are discussed in detail in [6]).

In this paper we describe three small experiments designed to illustrate to the general public how the problem of duality arises and how it is solved in the modern interpretation of the nature of light. At the same time, terms like *photon*, *quantum*, *light particle*, and *interference* can be introduced. In particular, the experiments show (1) the particle nature of light by producing an audible click for each detected photon; (2) the wave nature of light by showing the far-field diffraction pattern from a double-slit; (3) a double-slit experiment with very weak light and an image-intensified CCD camera as a detector, showing in real time the arrival of individual photons and the gradual build-up of the diffraction pattern. These hands-on experiments have been designed to be robust and tutorial enough to be shown in exhibitions for the general public or for students from junior high school level upwards. Each experiment fits comfortably into a table space of $25 \times 100\ \mathrm{cm}^2$. Special attention has been given to stray light suppression so that the experiments can be run in full sunlight or under the glare of museum spotlights. This last aspect in particular sets our apparatus apart from previous work where the setup is hidden inside a stray light shield [7] or operating in a dark room [8], or from [9, 10] where the setup was designed with a physics laboratory course in mind.

We also describe an alternative, much less expensive setup as a replacement for experiment 3 with its expensive camera system. This version would be the one most likely to be realizable within the tight constraints of a school budget.

2. Pedagogical Idea

The design of the experiments was partly inspired by the superb "Physics 2000" web site developed at the University of Colorado [11] which is also available in Spanish [12] and was translated into German by us [13]. The pedagogical idea is first to give the audience convincing proof of the particle nature of light. The second step is to predict the intensity pattern behind a double slit, based on light as a stream of particles: two bright lines. This is in obvious contradiction to the observed pattern that consists of many bright and dark lines and proves the wave nature of light. We have found that this contradiction piques the curiosity of the audience and makes them wonder how scientists solved that problem of duality [14], a term that many people have heard before without really understanding its significance. As a third step we then show how the diffraction pattern of a light wave is, in fact, built up through the arrival of many individual photons. One can even go a step further and strike an analogy to quantum theory in general where an individual event (like the arrival of a photon at a specific spot on the screen at a specific time) cannot be predicted, only the average behavior can (here the formation of a pattern of bright and dark stripes in a particular position on the screen). In the following we will describe the three experiments in detail.

3. Experiment 1: Hearing Single Photons

The experimental setup is shown in figure 1. The light from a red diode laser module (laser pointer) is attenuated by neutral density filters and enters a stray light filter mounted in front of a photomultiplier module (No. 5784 by Hamamatsu Photonics). This module is operated on a ±15 V supply and contains the high-voltage supply for the photomultiplier, the voltage divider network for the dynodes, and a preamplifier that brings the signal pulses up to about 1 V in amplitude. The interior of the stray light filter, a "light baffle", is also sketched in Fig. 1. It is painted black inside and contains a series of 2 mm apertures, another strong attenuator and two interference filters that pass the red light only.

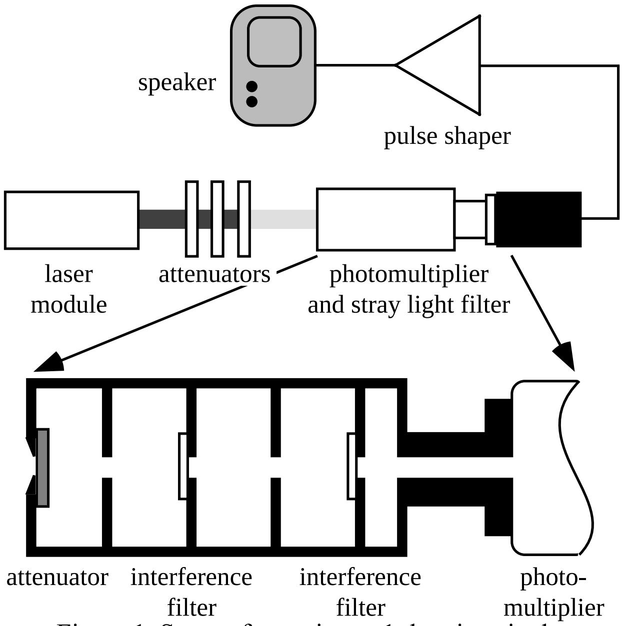

Figure 1. Setup of experiment 1: hearing single photons (not to scale)

With this combination of filters and attenuators the 1 mW laser output power is reduced to a level where the photomultiplier can resolve individual photons. A discriminator selects only high-amplitude pulses in order to suppress the dark counts (Fig. 2). A monoflop lengthens these pulses to 0.5 ms so that they give a more pleasant and impressive sound on an active loudspeaker. The whole setup is covered by a transparent plexiglass hood in order to prevent visitors from looking into the laser beam or touching the optical and electronic components.

When in operation the speaker emits an irregular series of single clicks while the laser is turned on. Interestingly, the random clicking sounds remind most visitors of the clicking of a Geiger counter which they have seen in science museums, lectures, or in movies. The visitor can turn the dial of a potentiometer in order to vary the laser power and listen for the corresponding change in click rate. We find it very important that the visitor can check that this is an honest experiment and not an electronic simulation connected to the laser power dial. Two mechanical beam blockers can be operated by buttons mounted on the outside of the protective plexiglass cover over the setup. Pressing one of these buttons (which clearly have no electrical connection to the rest of the setup) pushes a piece of cardboard into the beam, thus blocking it and stopping the clicking. One of the blockers is located in front of the attenuators so that the red laser spot can be seen on it when it blocks the beam. On the second one, positioned behind the attenuators, the spot is much too weak to be seen with the naked eye. This visual feedback is also the reason for the ordering of the attenuator plates on the basis of increasing opaqueness: on the surface of the second one a red spot can still be seen, much weaker than on the surface of the first one.

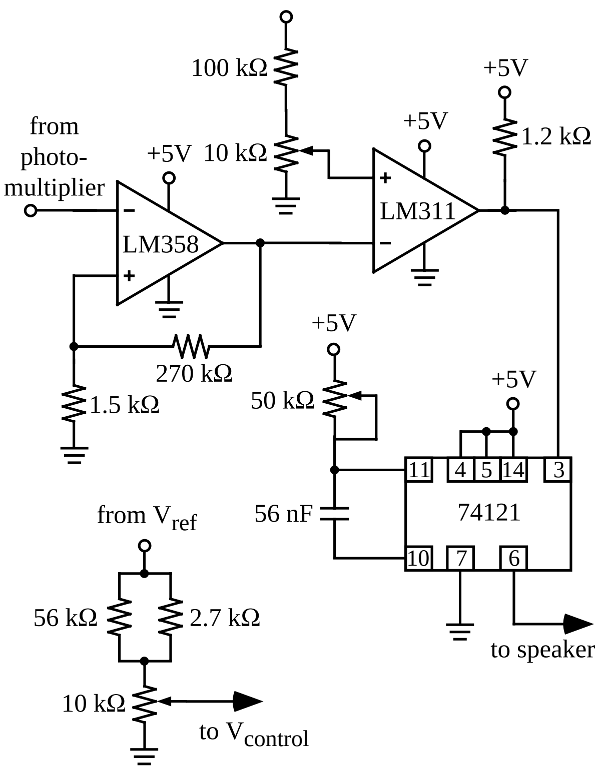

Figure 2. Circuit diagrams for experiment 1. Except for the photomultiplier module a single +5 V supply is sufficient, making interfacing with the monoflop (74121) easier. V_{ref} and $V_{control}$ are two of the connector pins of the Hamamatsu 5784 photomultiplier module.

In principle, of course, a laser is not required for this experiment; any light source could do. However, there are two reasons for using a laser source here. First of all, it is important to use the same light source as for the following two experiments because otherwise a visitor could suspect that light coming from that particular type of light source consists of particles while the laser source used in the diffraction experiments emits waves. Secondly, the photomultiplier is extremely sensitive to stray light and must be suitably protected if the experiment is to be operated under ambient illumination levels. The two interference filters provide some spectral filtering, and the directionality of the laser beam allows us to use light baffles as a spatial filter: only light directed exactly along the axis of the setup can reach the photomultiplier. Note that such a light baffle is superior to just a long narrow tube because photons scattering in the first few sections have a low chance of advancing further towards the detector before being absorbed by the blackened walls.
Alignment of the setup is somewhat tedious because — in order to keep the setup as simple and uncluttered as possible — no mirrors are used that could help to direct the laser beam precisely through all apertures inside the stray light filter. Once properly aligned, however, the photomultiplier voltage and the threshold can be chosen such that even under normal lighting conditions clicks can be heard only with the laser turned on, apart from just a few background clicks per minute. We should further note that the speaker volume must be chosen wisely, especially if one has to stand next to the experiment for several hours!

4. Experiment 2: Diffraction from a Double Slit

This experiment is the standard setup for the observation of diffraction from a double slit (Fig. 3). The same type of laser module (this time always run at its full power of 1 mW) illuminates a black slide with two 0.1 mm wide slits separated by 0.25 mm. The commercial slide we used for this purpose contained three different double slits; each pair was visible to the naked eye only as a bright line on the dark slide. We found it important to block the two unused slit pairs with black cardboard in order to avoid confusion of the visitors as to what the double slit really is: many were confused by something called *double*-slit but seemingly consisting of *three* transparent slits, and only one of them being illuminated by the laser. For further illustration, an identical slide is mounted atop a red light source just under the top of the plexiglass cover, with a magnifying glass close by.

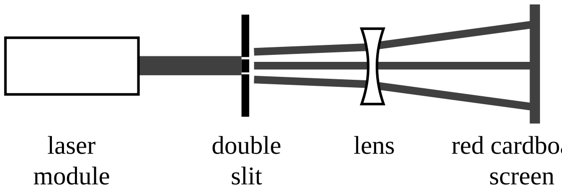

Figure 3. Setup of experiment 2: diffraction from a double slit (not to scale)

The diffraction pattern is viewed on a cardboard screen. The use of a red screen is preferable to a white one because under daylight illumination only the red part of the ambient light can reduce the visual fringe contrast by filling in the dark areas of the pattern; on a white screen *all* ambient light would help to spoil the contrast. The presence of the lens ($f = -50$ mm) is not ideal from a pedagogical point of view. Some visitors suspect that it is the action of the lens that makes the light behave like a wave; after all, there was no lens in the experimental setup showing particle behavior of light! However, we found it necessary to magnify the fringe pattern for easier viewing. In principle, one could add a mechanism to move the lens in and out of the beam or view the pattern through a magnifiying glass. This latter option has the serious drawback that only one person at a time can view the pattern and that one does not have the eye-catching large red stripes to draw a visitor's attention to the experiment.

We chose a double slit over a single slit because it is easier to see several bright and dark stripes, which provides a better visual impression. Seeing many bright stripes stresses the difference from the expectation based on the particle theory of light, i.e., just two bright “shadows” of the slits. It is also more difficult to explain diffraction from a single slit in a hand-waving fashion than for a double slit where the two interfering sources are immediately evident to the visitor.

5. Experiment 3: Single Photons Forming a Diffraction Pattern

This is almost the same setup as in the previous experiment, except that the lens and the screen have been replaced by a sensitive image-intensified CCD camera (Theta System) that is read out by a computer (Fig. 4). The laser beam is attenuated to 45 nW *before* reaching the double slit. Since the Gaussian laser beam has a diameter of about 2 mm, only 1/12 of the laser power can actually pass through the narrow slits, or about 1.2×10^{10} photons per second. This corresponds to an average distance between two photons of 2.5 cm. Since the slide with the double slit is only 150 μm thick the setup clearly constitutes a single-photon diffraction experiment, with all the philosophical difficulties this implies in the particle picture [14]. It is therefore a modern, real-time version of the heroic experiments by G. I. Taylor where exposure times of up to three months were used in an investigation of single-photon diffraction with photographic light detection [15].

In order to be able to resolve the arrival of individual photons on the CCD camera more attenuators were placed inside the tube covering the intensifier aperture, as well as two red interference filters. The intensifier is very insensitive for the red light, which helps to reduce the number of attenuators needed in order to protect it from playful visitors who try to shine their own red laser pointers into the camera (you never know!); furthermore, the way the components are geometrically arranged they could do that only at an angle, making the interference filters more opaque even for the red light. This is of particular concern here because light baffles like in the first experiment cannot be used since an image must be formed. The overall attenuation between double slit and CCD chip is about 3×10^8 so that a few tens of photons are detected in an exposure time of 20 ms. This single-photon detection is only possible because of the extremely low dark count rate of 20 electrons/(s cm^2) of the uncooled imaging system. When the ambient temperature rises a weak haze can be seen across the accumulated image, due to thermally emitted electrons from the image intensifier. This haze could be eliminated by cooling the imaging system with a Peltier element.

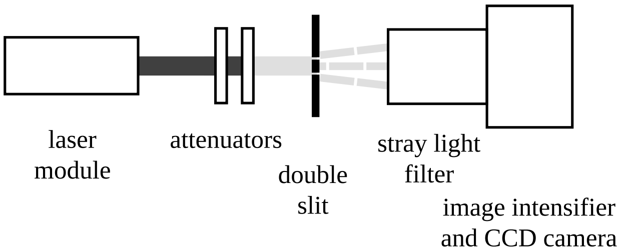

Figure 4. Setup of experiment 3: detecting individual photons in a single-photon diffraction experiment (not to scale)

One such 20 ms time frame from the CCD camera is shown in Fig. 5a. About 40 individual photons have arrived in the detection plane during this time interval with a seemingly random spatial distribution. When several such images are superposed, however, one begins to see the double slit diffraction pattern (Fig. 5b). On the computer screen the live image of the camera is shown in one window and the accumulated image in another one below the first. With the press of a button the visitor can clear the accumulated image and restart the integration, thus observing the gradual build-up of the diffraction pattern through the arrival of individual photons. An impression of what those two live images look like as a function of time, go to the web page listed below [16] and watch the animated GIFs or the QuickTime movies there.

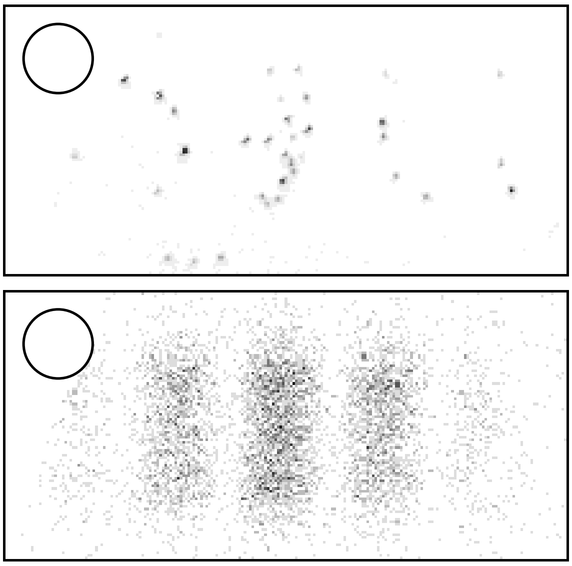

Figure 5. (a) A single 20 ms time frame of the CCD camera, showing several individual photon arrival points. (b) Image obtained after integrating for a few seconds: the diffraction pattern emerges. The gray-scale is different from that in (a).

One could argue that in this setup the photons are not really independent, since they come from a laser beam, i.e., a coherent state. However, the laser pointer is not stabilized in any way (in particular, it is running on multiple longitudinal modes), so that its coherence length is rather short, on the order of the average separation between photons. Also, if the experiment can be run in a darkened room one can remove some of the attenuators from the stray light filter and insert them between laser and double-slits. If all attenuators are placed there and the system is then operated in a completely dark room an effective separation of two photons of 7500 km can be achieved without loss of count rate on the detector.

In summary, this experiment is a single-photon diffraction experiment in two respects. On the one hand, each photon is alone near the double slits. On the other hand, out of the many photons passing the slits only very few can pass through to the detector so that also the detection occurs on the basis of individual photons. In this sense, there are two demonstrations of duality in one experiment!

6. An Alternative, Low-Budget Approach to Single-Photon Diffraction

The single photon experiment is very impressive and instructive but also very expensive to realize. A more affordable way to demonstrate the coexistence of wave and particle properties is provided by the setup sketched in Fig. 6. This is basically a combination of Experiments 1 and 2, connected by a glass plate as a beam splitter.

The weak power reflected by the uncoated glass plate is further attenuated before reaching the double slit. The single-photon detector is mounted on a translation stage that allows one to shift it sideways such that the small aperture at the detector entrance scans across the diffraction pattern. At the same time, a marker rigidly attached to the translation stage points to the corresponding position of the full-power diffraction pattern visible by eye on the cardboard screen next to the detector. Moving the detector modulates the audible click rate in step with the brightness at the tip of the pointer.

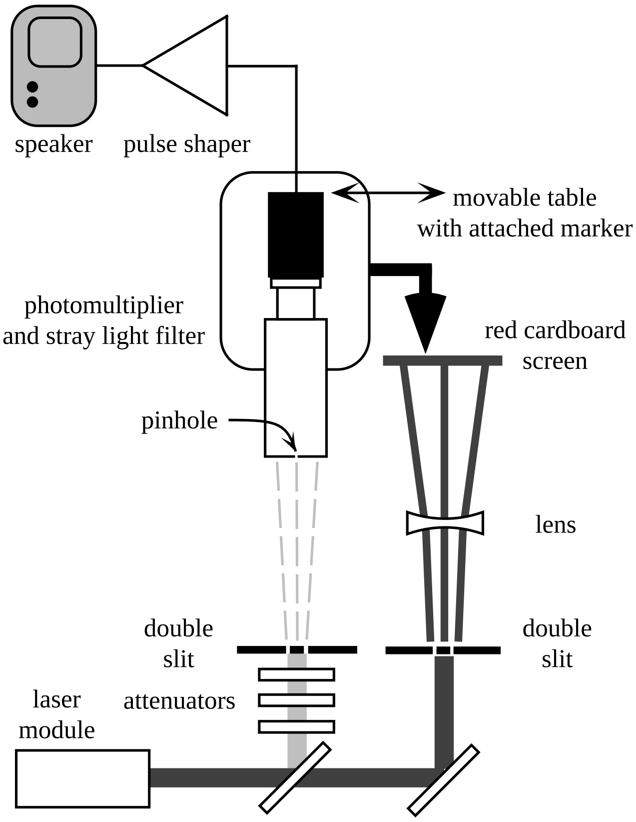

Figure 6. Setup of a low-budget version of the single-photon double-slit interference experiment

Once again it is important to keep the setup as clean and transparent to the visitor as possible. In particular, it must be absolutely clear that there is no electrical connection between the translation stage and the detection electronics, so that nobody can suspect any electronic trickery.

Attractive as this low-budget approach is for the construction of a demonstration setup in a school environment one should keep in mind that it introduces another concept, that of a beam splitter. For the average person that is not a problem (we all know the partial reflection from a window pane). But from a quantum optics point of view, a beam splitter is a tricky device full of theoretical and philosophical problems, particularly when illuminated with single photons [6]. Just to give an idea here, one runs, for example, into the same apparent problem as with the double slit: which way does the photon go?

7. The Key Experiment: Covering One of the Two Slits

A very impressive little experiment is to position the detector in the first minimum near the center of the double-slit diffraction pattern and then to cover one of the slits with a piece of cardboard. The detector is now almost at the center of the single-slit diffraction pattern, and a large rate of clicks is the result. This way of operation brings out the conceptual problem underlying the double-slit interference: although less area is available for the light to go through, the detected light power goes up dramatically.

This kind of experiment can, of course, also be performed with the camera experiment 3. However, we find the realization with this low-budget setup much more impressive because the clicks are commonly regarded as a more direct way of detection than watching dots on a computer screen. For the solution of the wave-particle problem, nonetheless, watching the genesis of the diffraction pattern from single dots makes an impression that cannot be beaten.

8. Conclusion

It is more than one hundred years ago now that Max Planck delivered the historic talk in which he announced his new formula for the blackbody radiation spectrum [17]. Among the many commemorative events held in Germany for the centennial of quantum theory in the year 2000 was an exhibition with the title “h heute” (“h today”), hosted by the Deutsches Museum Bonn [18]. It was aimed at the general public and at highschool students and had the purpose of explaining in understandable terms the essence of quantum mechanics and its influence on modern science and everyday life. The basic idea was to provide hands-on demonstrations of quantum mechanical phenomena and in this way dispel some of the mystery that shrouds it in the public eye. Apart from the wave-particle duality experiments there were other exhibits, such as the storage of single particles in traps, scanning probe microscopy, femtosecond spectroscopy, and superconductivity, to name just a few.

The experiments described here (Fig. 7) were shown as part of that exhibition. They have also been shown on various other occasions, from hands-on demonstrations for high school students or for their teachers to a public exhibition in a big tent on the town square of the city of Bonn, with particular appeal to the media, from newspapers to radio and TV shows.

On all these occasions we have been overwhelmed by the enthusiastic response of the non-scientific public. There seems to be a genuine need for everyday people to learn about what scientists are doing. It is certainly quite a different challenge to step out of the laboratory and to explain the essence of quantum theory to the man and woman on the street than to explain it to university students assembled in a lecture hall. But in a certain sense it is even more rewarding because some of the questions and suggestions about the wave-particle dualism, coming from a very different point of view and background of experience, were really original and sometimes quite challenging.

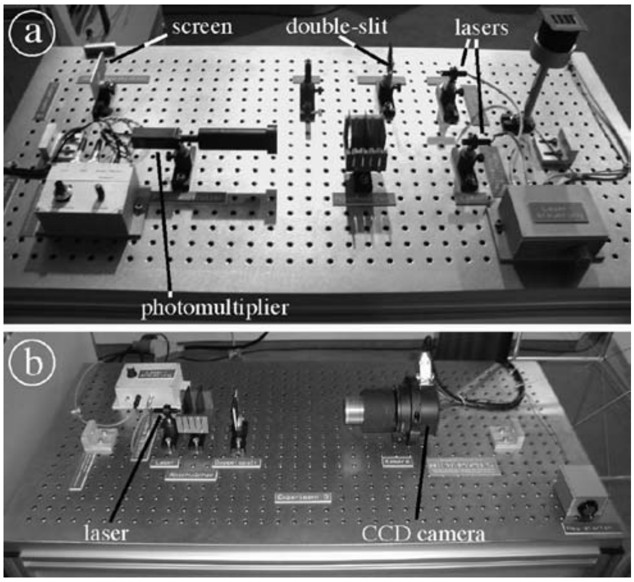

Figure 7. Photographs of the complete setups with their plexiglass covers removed. (a) Experiments 1 (front of table) and 2 (back). Laser beams go from right to left. (b) Experiment 3. Laser beam goes from left to right.

9. Acknowledgment

The funding of the parts and supplies needed for the realization of the demonstration experiments would not have been possible without the relentless efforts of D. Meschede and E. Lahr-Nilles (Bonn University) in connection with the “h-heute” exhibition. We extend our very special thanks to T. Tatarczyk from Theta System Elektronik in Gröbenzell, Germany, for the generous loan of the image-intensified camera and the accompanying software. We also thank D. Haubrich for assistance with the camera software and the electronics workshop at Bonn University's Institute for Applied Physics (where we performed part of the work described here before moving to Fribourg) for help with the construction of the electronics hardware for the experiments.

Appendix

Here we present a list of possible suppliers for the parts that went into the construction of the experiments. This list reflects our particular choice which was often dictated by convenience or circumstance. We do not wish to imply that other parts or suppliers would not be equally suitable.

- Diode laser modules: LAS63/01-L by CONRAD (http://www.conrad.com). An American equivalent to this electronics store would be, e.g., Radio Shack. The laser light has a wavelength of 635 nm which is easily visible. The modules run from a single +5 V supply and have an extra input pin that can be used to reduce the output power from its full value of 1 mW just with the addition of a 10 kΩ potentiometer.

- Attenuators: Neutral density filters distributed by Coherent Inc. (http://www.coherentinc.com). Any optics supplier carries similar neutral density filters.
- Band pass filters for λ = 632.8 nm with a bandwidth of 11 nm: No. 42-5421 by Coherent Inc. (http://www.coherentinc.com).
- Photomultiplier module: No. 5784 by Hamamatsu Photonics K. K. (http://www.hpk.co.jp/Eng/main.htm).
- Active loudspeakers: carried by any consumer electronics or computer store.
- Double slits: No. 469-84 from Leybold Didactic GmbH (http://www.leybold-didactic.de), a supplier of equipment for teaching laboratories in educational institutions.
- Intensified CCD camera: this is a *very* expensive device (> 10 000 $). We were lucky to receive it as a free loan from Theta System Elektronik GmbH (http://www.theta-system.de) who even modified the software to suit the needs of a public exhibition.

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