

Interactive screen experiments with single photons

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Abstract

Single photons are used for fundamental quantum physics experiments as well as for applications. Originally being a topic of advance courses, such experiments are increasingly a subject of undergraduate courses. We provide interactive screen experiments (ISE) for supporting the work in a real laboratory, and for students who do not have access to a quantum optics laboratory. The main focus of the ISE is on undergraduate education, but some of the experiments are suitable for other levels of higher education as well.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Elementary courses on quantum physics are predominantly oriented to the historic development of the theory. Consequently, lecture demonstrations include ground-breaking experiments such as photoelectric effect [1], Franck–Hertz experiment [2] and Compton effect [3]. Modern research on the quantum physics of light and matter is usually taught in advanced courses, often at graduate level, although some of these experiments are dealing with quite fundamental issues of physics and would be interesting to undergraduate students and non-specialists as well. Consequently, monographs appeared which present fundamental experiments on complementarity, entanglement and quantum information to readers at the undergraduate level [4, 5].

Recently, undergraduate students' laboratories on quantum optics have been established [6–10] and a complete demonstration setup is now commercially available [11]. This development was strongly supported by technical breakthrough in short wavelength diode lasers as a substitute to bulky gas lasers, since it is now possible to equip a students laboratory with a regular budget. Despite the reports on successful implementation of modern quantum

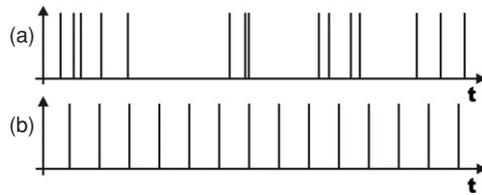


Figure 1. Counts observed with a photomultiplier tube or avalanche photo diode: (a) Poissonian count distribution from a monochromatic electromagnetic wave, i.e. laser light; (b) anti-bunched counts from nonclassical light.

physics experiments, only a small fraction of physics students actually has access to such laboratories, and the access is restricted in time to the duration of a course.

We provide multimedia representations of several fundamental quantum optics experiments to the public as interactive screen experiments (ISE) [12]. The ISEs are not meant as replacements for real experiments; they are suitable for students who otherwise would not be able to work with this type of experiment, and for preparing and recalling real laboratory work. In the following section we recall the physics of the photon [13, 14] and describe preparation of single photon states as a basis for explaining our experiments. In section 3 we evaluate the photon as a concept for introductory courses. Implementation of interactive screen experiments is described in section 4. In section 5 we give a short overview on advanced experiments with single photons possible with our setup.

2. Photons as quantum objects

2.1. Quantized electromagnetic field

The photoelectric effect is often called a demonstration of the quantum nature of light, since it played a leading role in the early development of quantum physics [15]. However, within the formalism of quantum physics, absorption and emission of light is described as quantum jumps of atoms disturbed by a classical electromagnetic wave. Many publications in the 1960s pointed out the power of this so-called semiclassical approach by describing complex quantum optical systems including, for example, the laser [16]. In fact the semiclassical approach was so successful that it was a major challenge to demonstrate its limitation in the low-energy regime of visible light. The first experimental evidence of nonclassical light, i.e. an experiment which cannot be fully explained within classical optics, was reported in 1977 [17]. Quantum optics is a major research field today. A review on detecting nonclassical light is given in [18].

2.2. Single photons

Very dim light is detected by photomultiplier tubes or avalanche photo diodes (APD). They produce an electron avalanche after absorption of one or several photons, which are called counts, or ‘clicks’ of the detector. The detection events of dim laser light represent a Poissonian process. Dim laser light and also thermal light are consistent with the semiclassical theory. Hence, the individual counts are no evidence for single photons. Nonclassical behaviour is associated with temporal anti-bunching. In the extreme case of perfect anti-bunching, the counts would occur at completely predictable times $t = t_0 + n\tau$ with a natural number n and a time constant τ . A predictable detection event corresponds to absorption of a single photon (figure 1).

2.3. *Heralded single photon states*

Generation of single photons on demand [19, 20] is technically challenging. Much easier is the generation of single photons at statistically varying points in time. In this case, the time coordinate is replaced by a coordinate of events, and it is valid to speak of single photon states. Prediction of photon generation is accomplished by simultaneously generating two photons within a coincidence interval using a cascaded atomic transition, or parametric downconversion, and detecting one photon to specify the time of event. The other photon is heralded by the gating event [21].

3. Single photons in physics education

An introductory quantum physics curriculum could be based on exemplary quantum objects of any kind, for example electrons, atoms, or photons. Elementary quantum physics of electrons is predominantly the replacement of classical mechanical motion by the dynamics of wave functions described by the Schrödinger equation. The quantum physics of light is derived from classical electrodynamics rather than mechanics and does not address motion of particles at all. Both quantum mechanics and quantum electrodynamics have characteristic traits in common, such as quantization of observables, stochastic outcome of individual measurement, state superposition, entanglement and decoherence.

Mechanics is directly connected to human physical experience, and craft. Therefore most teachers prefer mechanical analogies for an introduction to quantum physics rather than analogies from the abstract theory of electrodynamics. The usage of the term photon often implies particle properties of light. This mechanical approach creates substantial misunderstanding. Consequently, the use of the term photon has significantly changed with time [22]. Conceptual difficulties of the quantum theory of radiation including the term photon are reviewed by one of its pioneers [23].

The optical approach to quantum physics offers specific possibilities: many of the experiments on the foundations of quantum physics [5] are performed with light for technical reasons. Demonstration experiments with single photons for educational purpose are now available, including demonstration of entanglement [6, 10] and two-photon interference. Similar experiments with single electrons or single atoms are yet to be developed³. Qubits are the simplest abstract quantum states in a two-dimensional Hilbert space. They can easily be represented with optical experiments, for example by photon polarization or distinct optical paths. Qubits are fundamental to the emerging field of quantum information. Quantum cryptography has already gained public attention and the first systems are commercially available [26].

There is no undisputed answer whether optics—more generally electrodynamics—is a suitable elementary approach to quantum physics. We believe that the advantage of including demonstration experiments on the foundation of quantum physics and modern concepts of information technology justifies meeting the challenge.

4. Multimedia representations of single photon experiments

4.1. *Quantum physics representations*

For teaching quantum physics, simulations are particularly attractive: real experiments are much more complex than for other areas, and the principles of quantum mechanics are quite

³ So far, undergraduate experiments with atom traps use large ensembles of atoms [24, 25]. There is no pedagogical reason for not working with single atoms in undergraduate laboratories, but the demand on financial resources and qualified operators is beyond limit.

counterintuitive. Simulations can help students to build mental models and to get involved interactively [27]. However, there are challenges: several empirical studies on introductory quantum physics courses accordingly report that avoiding classical analogies helps to obviate misconceptions [28–30]. Therefore, visualization of quantum phenomena has to be designed very carefully [31]. Ideally, students should have been trained in interpreting simulations with respect to reality before using this tool for quantum physics. Within the large supply of simulations available, there are some which do not fulfil accepted quality criteria [32].

Apart from these issues, which can—and have been—addressed successfully, simulations are principally not suitable for showing how knowledge was derived from observation. Simulations are optimized to an idealized view on how nature would behave according to the accepted theory. Only a real experiment can motivate how scientists evolved the quantum theory. Key features of a real experiment can be communicated with a video, or with an interactive screen experiment. The latter has several advantages: students can interactively manipulate the experiment and try out different settings, the speed of representation can be adjusted by the student, and additional information can be retrieved on demand. A remote controlled laboratory [33] would exhibit additional authenticity, but for realizing different experiments simultaneously, enormous resources would be required.

4.2. Experimental setup

Our experimental setup is intentionally based on components used in modern research laboratories. We emphasize a clear geometry, where the beam path can be followed easily and individual optical elements can be recognized. Photon pairs are generated by parametric down conversion (PDC). An incident pump photon is converted into a pair of so-called signal and idler photons by nonlinear optical interaction in a dielectric medium with an efficiency of 6×10^{-11} . Our pump laser (PicoQuant LDH-P-C-405M) emits 60 ps long laser pulses every 62.5 ns with 2 W peak power and 403 nm wavelength. PDC photons are generated in a 3 mm long barium beta borate (BBO) crystal. The PDC emission is 3° off the optical axis and the wavelength of both photons is around 806 nm within a certain spectral bandwidth. PDC photons are detected with fibre coupled avalanche photo diodes (PerkinElmer SPCM AQ4C). The APD detectors have a quantum efficiency of 48% at 810 nm and a dark count rate of 300 s^{-1} .

For data acquisition we use a time-digital converter module (Acam TDC-GPX). The laser electronics emit an electrical trigger pulse which defines a 2 ns broad time gate for possible detection. By gating, the rate of observed dark counts is reduced to 15 s^{-1} . With the repetition time of 62.5 ns the detectors are given enough time to recover after a detection incident.

Single photon experiments are obviously very sensitive to background illumination. Our detectors are protected by bandpass filters ($800 \pm 40 \text{ nm}$) against diffuse light. There are no other light sources in the laboratory except white LED modules, which do not emit in the bandpass wavelength range. The running experiment can be explained in the lab at bright LED light to students and it can be photographed. The bright photos of the experiment in the ISE are therefore realistic.

4.3. Coincidence rates versus single events

The method of heralded single photon state preparation implies that one of the PDC photons is detected first and the other photon is available for further experiments (figure 2). However, the spatial separation of two detectors (40 cm) is smaller than the product of time resolution times speed of light. Therefore, a coincidence event of two detector ‘clicks’ is taken as preparation

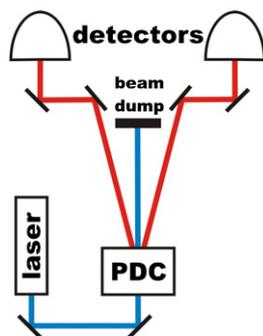


Figure 2. Principle of the experiment ‘coincidence measurement’.

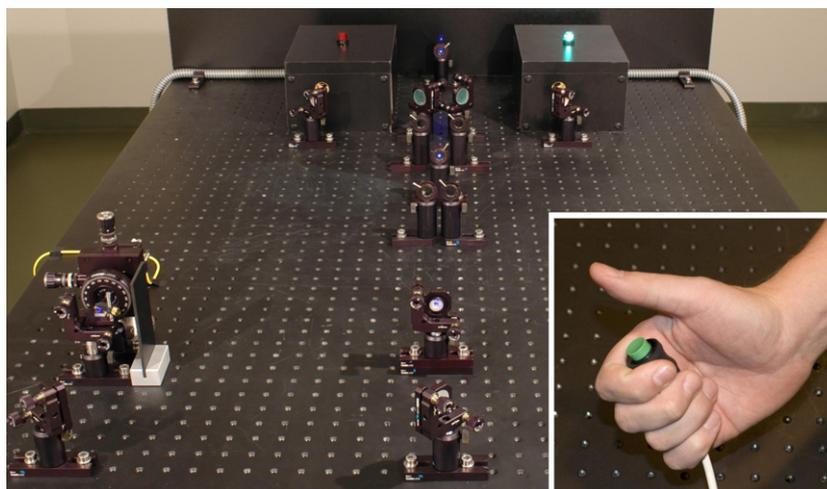


Figure 3. Experimental setup for coincidence measurement with visual indicators on the detector boxes and enlarged push-button for starting the single measurements.

and detection of a single photon state. With our setup, we obtain single ‘clicks’ at each detector up to 43 kHz and coincidence rates up to 10 kHz.

In didactic literature, the conundrum of quantum physics is illustrated based on single events rather than technical coincidence rates [34]. Accordingly we can run our experiment in single event mode. Without being evident to the observer, laser pulses are repeated until the first event is detected and the experiment is stopped. The result is then visualized by LEDs on top of the detector boxes, as shown in figure 3. The experiment can be started again with a push-button. Due to the high laser pulse rate, the experiment appears to work instantaneously.

4.4. Production of interactive screen experiments

The first step in developing an interactive screen experiment is to set up the real experiment and take data for all settings which are accessible in the ISE. Then the experiment is turned off and for each setting, a photograph is taken with studio illumination. We use conventional diffuse incandescent bulbs of 200 W electrical power each, and a 90 W halogen spot light. The camera is a Nikon D70 digital SLR with a 28 mm $f/2.8$ lens stopped down to $f/11$.

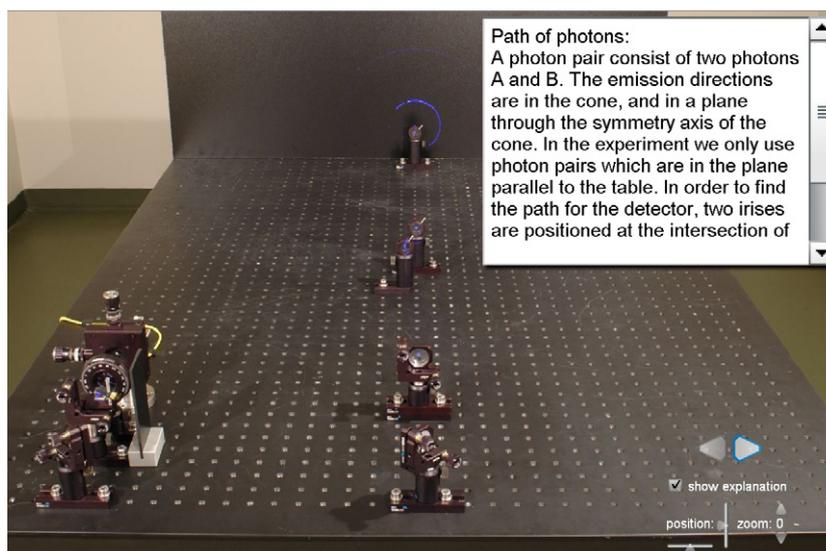


Figure 4. Interactive screen experiment ‘setup’ with enlarged explanation. At the end the experiment is ready to observe coincidences.

This choice yields a normal angle of view and sufficient depth of field over the entire optical table. Exposure times are of the order 4 s at 200 ASA sensitivity and tungsten light white balance. All images are saved in uncompressed NEF format. Present technology urges us to limit the file size of an ISE to less than 10 MB. Therefore, the images are scaled down from 3008×2000 pixels to 1504×1000 pixels and saved in the JPEG format at 80% reduction level. For every principal view, a master image is generated and the changing areas are cut out from the subsequent images. All layers are combined in Adobe Flash 9. Each set of layers is associated with the corresponding data obtained in the real experiment. In every ISE the beam path can be shown and the pictures can be zoomed for details.

Even the basic setup for showing evidence of nonclassical light (see section 4.7) already has 18 variable optical components. Obviously, it is not feasible to include all degrees of freedom in a single ISE. Moreover, we would like to give teachers the choice of emphasizing specific issues. We have therefore created separate ISEs on specific topics.

4.5. ISE: optical setup

The first ISE starts with the empty optical table. In the subsequent frames of the ISE, additional components appear (or disappear) upon clicking the grey arrow buttons (figure 4). For every new optical element that appears in the frame, short explanations are available as inserts. It is beyond the scope to elucidate optical components such as polarizing beam splitters and $\lambda/2$ waveplates in detail. Their basic function is explained, their appearance in the optomechanical holder can be realized, and the principal idea of the setup can be understood.

4.6. ISE: coincidence method

As pointed out above, the detectors do not respond to every photon generated. Since our goal is an authentic representation of real experiments, we have dedicated a separate

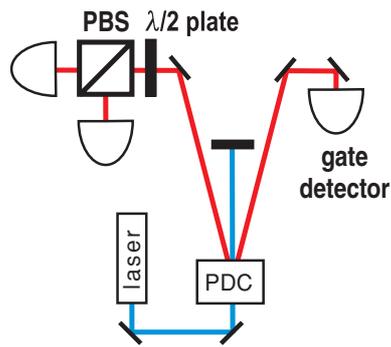


Figure 5. Principle of the experiment ‘existence of the photon’.

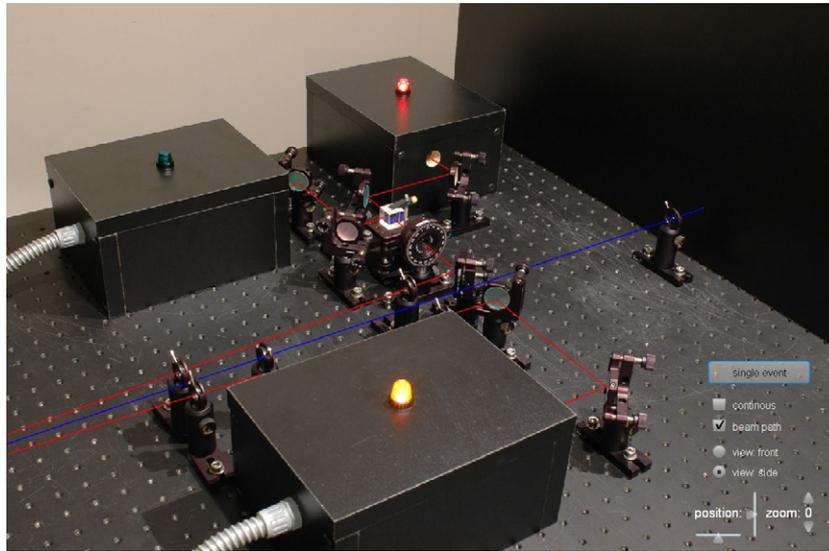


Figure 6. Interactive screen experiment ‘existence of the photon’ with single events. The side view is selected and the beam path is shown.

ISE to the principle of coincidence measurements. The experimental setup is shown in figure 3. The corresponding ISE can be run in the single event mode by a trigger button. Each single event is indicated by the LED on the corresponding detector box. We emphasize that only coincidences of both detectors are taken as events in later experiments. In a different version of this ISE, the coincidence rates are shown as a function of time. The rate is constant on average, but varies slightly due to the stochastic process of PDC generation and detection.

4.7. ISE: photons exist

With the casual term ‘photons exist’ [8] we mean to demonstrate the quantized nature of light. Following the experiment by Grangier *et al* [35], heralded photons pass a beam splitter. The optical beam path is shown in figure 5 and the actual ISE with single event mode is shown in figure 6. With the $\lambda/2$ -plate we rotate the polarization of the photons to 45° . The combination

of the $\lambda/2$ -plate and the polarizing beam splitter (PBS) is equivalent to a beam splitter with 50% transmission and reflection. After we have told the truth about detection efficiency in the ISE on the coincidence method, we now look at coincidences only. In the single event mode, exactly one of the two detectors behind the beam splitter detects the photon which has been heralded by the gate detector on the right hand.

Another ISE addresses the problem of simultaneous generation of two photon pairs within the coincidence interval. Since the gate detector does not resolve photon numbers, these double pairs affect the quality of the single photon source. A double photon can be detected behind both output ports of the beam splitter simultaneously. A quantitative measure for the purity of single-photon events is the second-order correlation function $g^{(2)}(0)$ [13, 14]. For a classical monochromatic electromagnetic wave, $g^{(2)}(0) = 1$. Non-classical or quantum light is observed when $g^{(2)}(0) < 1$. We have obtained $g^{(2)}(0) = 0.0009 \pm 0.0004$, which violates the classical limit by more than 2000 standard deviations. In the related ISE the second-order correlation function is available for the experiment either with or without the gate detector.

5. Further experiments with single photons

The source of heralded single photons can be used for various fundamental quantum physics experiments, which also have been implemented as ISEs [36]. In some cases the setup is split into two parts. The heralded single photon source is then fed into a polarization maintaining optical fibre and delivered to the actual experiment. So far, we have covered five types of experiments: (A) classical optical results such as Malus' law or Michelson's interferometer are confirmed with single photons. The classical intensity variation is replaced by the coincidence rate. (B) Proof of non-locality with entangled photons according to the CHSH [37], Wigner [38] and Hardy [39] schemes. (C) Two-photon interference after Hong, Ou and Mandel [40] as an example of a quantum interference which cannot be explained in terms of wave optics. (D) Principle of quantum cryptography using the BB84 protocol. (E) Experiments on the photon statistics of light [41] up to a photon number of $n = 4$. The development of additional ISEs is in progress; technical details will be reported elsewhere.

6. Conclusion

Interactive screen experiments can help students to prepare and discuss real laboratory work, and they provide insight into the principles and technology of modern quantum optics experiments to a wide audience.

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