Fifteen years of quantum optics, quantum information, and nano-optics educational facility at the Institute of Optics, University of Rochester

Svetlana G. Lukishova*
University of Rochester, The Institute of Optics, Rochester, New York, United States

Abstract. The quantum optics/quantum information and nano-optics educational laboratory facility (QNOL) at the University of Rochester (UR) is located within three rooms of the Institute of Optics with a total area of 587 ft^2. It has been used for teaching a 4-credit-hour QNOL class annually for 15 years. Four teaching labs were prepared on the generation and characterization of entangled and single (antibunched) photons demonstrating the laws of quantum mechanics: (1) entanglement and Bell's inequalities, (2) single-photon interference (Young's double slit experiment and Mach–Zehnder interferometer), (3) single-photon source I: confocal fluorescence microscopy of single nanoemitters, and (4) single-photon source II: a Hanbury Brown and Twiss setup, fluorescence antibunching. Further, based on QNOL, 1.5 to 3 h sturdy quantum "mini-labs" were developed and introduced into the required classes such that all optics students at the UR had experience with quantum labs. Monroe Community College (MCC) students participated in two mini-labs at the UR. Since 2006 to spring 2022, a total of ~850 students have utilized the labs for lab report submission (including 144 MCC students) and more than 250 students have used them for lab demonstrations. In addition, UR freshman research projects have become a very important educational activity in this facility. All developed materials and students' reports are available at http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/. We present a description of sturdy, universally accessible experiments that can be introduced into either a separate advanced class or into classes with a large number of students. Assessment methods, evaluation of students' knowledge, and their attitude toward their career in quantum information are discussed. © *2022 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.OE.61.8.081811]

Keywords: quantum optics laboratory; entanglement and Bell's inequalities; single-photon interference; Young double-slit and Mach–Zehnder interferometers; photon antibunching; Hanbury Brown and Twiss interferometer; confocal microscope fluorescence imaging of single nanoemitters.

Paper 20220151SS received Feb. 16, 2022; accepted for publication Jun. 28, 2022; published online Jul. 20, 2022.

1 Introduction

In science and engineering education, quantum mechanics is among the most challenging topics of modern physics, and students constantly struggle to master its basic concepts.[1–7] It has been applied to important technological problems, with enormously powerful computers and total communication security being the future goals of quantum information technology, which is an emerging market. Thus, the future workforce must be familiarized with these new concepts and must be provided with hands-on experience in instrumentation widely used in emerging technological areas (e.g., nanotechnology and biomedicine). The goal of the 15-year project is to reduce to practice certain abstract components of quantum mechanics by allowing the students to complete experiments at levels of increasing sophistication, in particular toward quantum computing and quantum communication. Learning the abstract theory from hands-on experiments with modern silicon photodetectors, charge-coupled device (CCD) cameras, and computer cards facilitates the understanding of "quantum weirdness" while providing students

*Address all correspondence to Svetlana G. Lukishova, lukishov@optics.rochester.edu

0091-3286/2022/$28.00 © 2022 SPIE

with a unique experience using state-of-the-art technology of photon counting, which they are expected to encounter at their future workplace.

This paper describes the design of the advanced laboratory and lecture courses on photon quantum mechanics, highlighting interesting and cutting-edge experiments that can be performed in one lab period.[8] Starting from the advanced laboratory level, quantum "mini-labs" that can be used for introductory laboratory levels both for science, technology, engineering, mathematics (STEM) majors and for nonmajors were developed. These mini-labs are universally accessible,[9] and certain experiments may be integrated into traditional theory courses on quantum mechanics and modern physics. Consequently, students can make a connection between theory and experiment.[9] Although photon quantum mechanics undergraduate teaching experiments have been already reported in the literature,[10–33] the novelty of this study is the description of state-of-the-art photon quantum mechanics experiments that can be routinely conducted in big classes, with everyday teaching of students' groups during 1.5 to 3 h of a lab time. Sturdy mini-labs experiments on recent advances of photon quantum mechanics were introduced into several lectures and lab courses of different levels of students' experience, from freshman to senior, including community college students.

One of the overarching recommendations of the President's Council of Advisors on Science and Technology[34] on transformation of undergraduate STEM education during the first two years in college involves providing support for replacing standard laboratory courses with discovery-based research courses. This study describes an approach to this strategy. Certain related experiences have been outlined in earlier publications.[35–41] Manuals, student reports, presentations, and lecture materials can be found on a specific website.[42]

In December 2018, the National Quantum Initiative Act[43] became a law, thereby establishing a federal program to accelerate quantum research and development for the United States' economic and national security, including the training of quantum engineers.[44–48] At the Institute of Optics, University of Rochester (UR), the first laboratory class on quantum optics and quantum information was started in 2006 in the author's research laboratory on single photon generation and characterization[49] enabled by the Army Research Office and National Science Foundation (NSF) material research instrumentation grants' support. Other important pieces of equipment were borrowed from Lukas Novotny's laboratory. Graduate student Anand Kumar Jha (now a quantum-optics professor at the Indian Institute of Technology, Kanpur) assembled the first versions of an entanglement teaching lab. With initial support from the UR Kauffman Foundation Initiative for entrepreneurship, one of the novel student assignments included the "Summary Business Plan" project (2006), wherein the entire group (eight students) developed a keen sense for a budget and cash flow, using internet information existing at this time on the market quantum information company.[42]

Supported by Carlos Stroud, director of the UR Center for Quantum Information, and two NSF educational grants (2007 to 2012), jointly with him, the third "nano-optics" pillar of the teaching facility emerged. The third NSF educational grant [jointly with Nicholas Bigelow, director of the UR Integrated Nanosystems Center (URnano)] further enhanced the nano-optics part of this class. The history of this facility is outlined in Ref. 35. Currently, four basic teaching lab experiments are located within three rooms (total of 587 ft^2) of the Institute of Optics. The technical elective courses Quantum and Nano-Optics Laboratory (QNOL) for undergraduate (OPT 253) and graduate (OPT 453/PHY 434) students have become popular. OPT 453 was made a compulsory class for a master's in optics degree focused on nano- and integrated photonics. Moreover, several students of these classes went on to become quantum-optics professors (Chitraleema Chakraborty, Mayukh Lahiri, Omar Magaña-Loaiza, Mehul Malik, Xiaofeng Quian, Zhimin Shi, and Heedeuk Shin).

Owing to the QNOL facility, all the Institute of Optics students have experience with quantum optics experiments introduced to the required classes through developed 1.5 to 3.0 h sturdy mini-labs. Furthermore, UR freshman research projects on quantum optics have also become an important educational activity on this facility.

Rochester Monroe Community College (MCC) students have also benefited from this facility. This project was developed in a collaboration with MCC professor P. D'Alessandris. MCC students participated in two 1.5- to 3.0-h mini-labs on photon quantum mechanics at the UR.

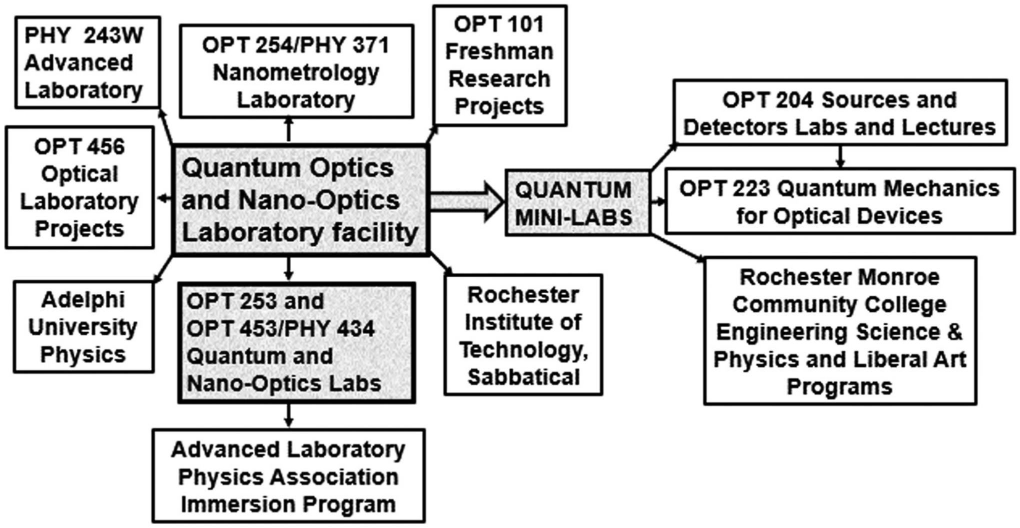


Fig. 1 Diagram showing all the conducted classes based on the Quantum and Nano-Optics Laboratory facility at the Institute of Optics, UR.

Since 2006 to spring 2022 inclusive, a total of ~850 students have utilized the labs for lab report submission (including 144 MCC students supported by three joint NSF educational grants) and more than 250 students for lab demonstrations. A framework shown in Fig. 1 presents all classes that used the QNOL facility.

In upper levels QNOL classes, four basic labs address generation and characterization of entangled and single photons, demonstrating the laws of quantum mechanics: (1) entanglement and Bell's inequalities, (2) single-photon interference (Young's double slit experiment and Mach–Zehnder interferometer), (3) single-photon source (SPS) I: confocal microscope imaging of single-emitter fluorescence, (4) SPS II: Hanbury Brown and Twiss setup, photon antibunching. In addition, weekly lectures with theory, discussion of lab equipment, measurements results, and the history of the cornerstone experiments in quantum optics form an important aspect of the QNOL classes. Figure 2 shows a structure of QNOL classes OPT 253/OPT 453/PHY 434.

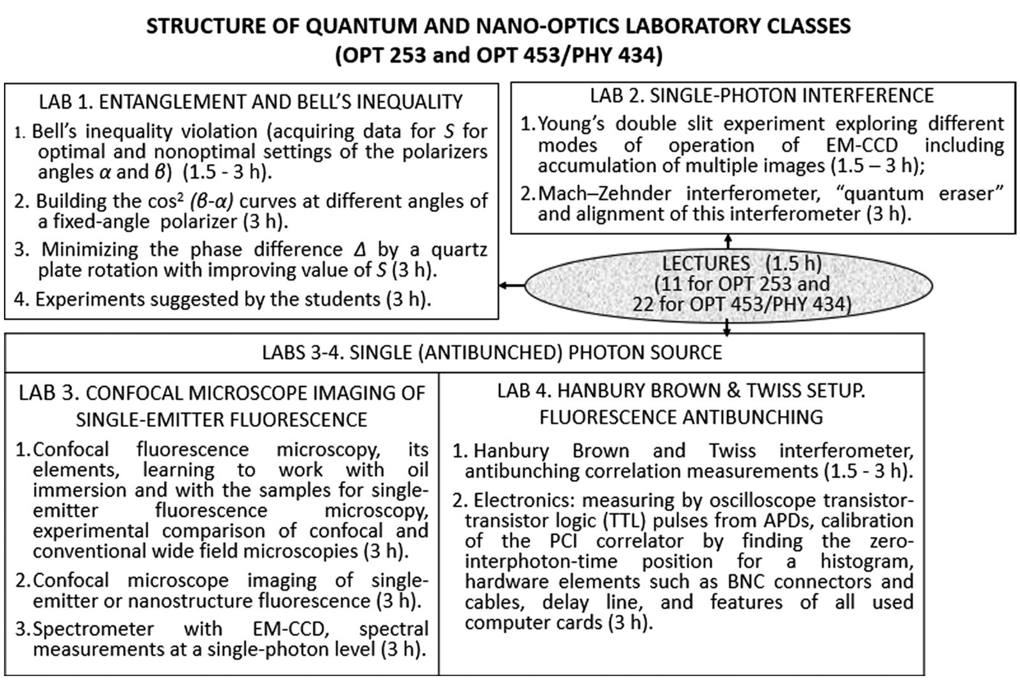


Fig. 2 Structure of the QNOL classes.

The remainder of this paper is organized as follows. Section 2 describes four basic teaching experiments of the QNOL classes. Section 3 outlines an approach of introducing quantum mini-labs to required undergraduate and graduate classes at the UR and to freshman quantum optics research projects. Section 4 presents a discussion on teaching MCC students and training professors from other universities and colleges at the UR QNOL facility. Section 5 presents certain pedagogical methods employed, evaluation of students' knowledge, and a discussion of students' attitudes toward their possible careers in quantum information after taking quantum mini-labs. Finally, Sec. 6 presents the conclusions of this study, lessons learned, and future plans.

2 Description of Four Quantum and Nano-Optics Teaching Experiments of QNOL Classes

QNOLs are one-semester, four credit technical elective courses comprising 11 1.5- to 3.0-h lab sessions, 11 1.5-h lectures for undergraduate students, and 22 1.5-h lectures for a graduate level class; it is also popular among undergraduate students. This class has no prerequisites and students are accepted starting from sophomores. Each of the four labs hosts 2 to 4 sessions, depending on the particular lab experiment. For undergraduate students, a final grade is provided based on three lab reports written in the style of a professional paper (the last two lab reports are unified into one lab report), maintenance of each lab session's journal, five question-quizzes before each lab session, and midterm and final quizzes. For a graduate level class, two additional graded assignments are included: essays on single and entangled photon sources and 20-min oral presentations of all labs results. With ~8 to 20 students in the class, teaching assistants (TAs) supervise groups of two to four students in the labs working as a team.

2.1 *Lab. 1. Entanglement and Bell's Inequalities*

Entanglement is the most exciting and mysterious property of certain quantum mechanical systems, where the property of one particle depends on that of another. Measurements performed on a first particle result in a change in the state of the second particle, regardless of how far apart they may be. This nonlocal character is key to entanglement, and propagation of any information must not occur. Entanglement can occur on one or more physical values—for example, polarization, energy, momentum, and time. Mathematically, in quantum mechanics, particles are called entangled if their state $|\Psi_{12}\rangle$ cannot be factored into single-particle states $|\Psi_1\rangle$ and $|\Psi_2\rangle$:

$$|\Psi_{12}\rangle \neq |\Psi_1\rangle \otimes |\Psi_2\rangle. \tag{1}$$

Several applications demand quantum entanglement, such as quantum computers, quantum communication, and quantum teleportation (teleportation of a state, but not of a particle).

During QNOL lectures, students learn the history of the idea of entanglement that was introduced into physics in 1935 by Einstein, Podolsky, and Rosen (EPR),[50] as a "spooky action at a distance," which was not believed by the authors (EPR), as information cannot propagate at any speed exceeding the speed of light. EPR also did not accept probabilities in the description of particle behavior. They suggested that quantum mechanics was an incomplete theory, and a future, complete theory of quantum mechanics would be like statistical mechanics with certain additional variables, which were later termed as "hidden." Shortly after the EPR paper, Schrödinger coined the word entanglement (*Verschränkung* in German) and further developed this concept.[51] Bohr replied to the EPR paradox paper indicating that it "contains an essential ambiguity when it is applied to quantum phenomena." He explained that from a perspective termed as "complementarity," "quantum-mechanical description of physical phenomena would seem to fulfill, within its scope, all rational demands of completeness."[52]

In the mid-1960s, the nonlocality of nature was realized as a testable hypothesis. In 1964, the mathematician John Bell showed that the "locality hypothesis" with "hidden" variables resulted in a conflict with quantum mechanics.[53,54] He proposed a mathematical theorem containing certain inequalities. An experimental violation of his inequalities would indicate the states obeying the quantum mechanics with nonlocality. However, Bell's inequalities (there are many types of Bell's inequalities, certain of which were obtained later by other researchers) are classical relations,[55] and they are violated only in quantum mechanics and only for certain values of parameters (e.g., under certain polarizer angles if entanglement in polarization occurs). For vast parameter spaces, both classical physics and quantum mechanics yield the same results without violating Bell's inequalities. Quantum correlation is a very rare event and not easily found. The most popular form of Bell's inequality for experimentalists is an inequality described by Clauser, Horne, Shimony, and Holt (CHSH) in their widely cited 1969 paper.[56] The CHSH inequality for polarization entanglement can be obtained from a trivial relation that modulus of sum is less or equal to sum of moduli. However, in a quantum world, this classical relation can be violated. It is impossible to understand based on "common sense" that the inequality $|a + b + c| \leq |a| + |b| + |c|$ can be violated; however, in this lab, students violate this inequality hourly by conducting only 16 measurements of coincidence counts at specific polarizers' angles calculated in Ref. 56.

The most popular approach to obtain entangled photons involves the use of a spontaneous parametric-downconversion (SPDC) process. This paper describes the sturdy lab construction on photons entangled in polarization for 1.5 to 3.0 h lab sessions of student groups. The original experiment was implemented by Kwiat et al.[57] To learn how to build a similar setup, further details can be found in papers[10,11] and books.[21,25,26] To learn about entanglement and Bell's inequalities, the books[58–63] can be recommended to the students, and SPDC can be understood from the book by Klyshko.[64] Ref. 12 is a well-organized database of references and websites (2014) on quantum optics teaching experiments including entanglement.

In the UR teaching lab, two polarization entangled photons are produced through SPDC in two type I beta barium borate (BBO) crystals pumped by a laser. For the past 15 years, three experimental setups with diode lasers (405 and 408 nm wavelengths λ) and a Spectra-Physics argon ion laser (363.8-nm wavelength) with an intracavity etalon inside have been used. In the SPDC process, a single pump photon spontaneously splits into "signal" and "idler" photons with longer wavelengths inside a nonlinear crystal. The efficiency of this process is only $\sim 10^{-10}$. Because of the spontaneous process, the angles of emitted photons and their wavelengths may have any values obeying the conservation of energy and momentum, such that SPDC photons, like those in a rainbow, have various wavelengths. To create an entangled state at 2λ wavelength (e.g., 727.6 nm for an argon ion laser pump and 810 and 816 nm with diode lasers), definite angles of signal and idler photons' propagation and narrow-bandwidth interference filters are selected. The signal and idler photons from each crystal with 2λ wavelength are emitted in a cone in the case of noncolinear interaction.

Type I SPDC implies that the signal and idler photons have the same linear polarizations, which is opposite to that of the pump photon. Two identical type I BBO crystals are used as the source of entangled photons, mounted back-to-back with optical axes orthogonally oriented. In this arrangement, each crystal can support SPDC of one pump polarization, and the other polarization simply passes through the transparent crystal. Further, a 45-deg polarized pump photon can downconvert in either crystal, producing a polarization entangled pair of photons. Mathematically, it can be represented as

$$|H\rangle + |V\rangle \rightarrow |V_s V_i\rangle + \exp(i\Delta)|H_s H_i\rangle, \tag{2}$$

where V and H represent horizontally and vertically polarized photons, respectively. Signal and idler photons are denoted by subscripts s and i, respectively, and Δ is a phase difference after two crystals owing to different path lengths for different downconverted polarizations in birefringent BBO crystals.

SPDC photons with horizontal and vertical polarizations are produced in different crystals; thus, they are independent of each other. Moreover, two overlapping cones of downconverted photons with vertical and horizontal polarizations yield a cone of unpolarized photons, although correlations in polarizations are to be measured. A cross-section of a cone of downconverted photons of one 727.6-nm wavelength selected through a 10-nm transmission filter recorded by an electron multiplying (EM)-CCD camera iXon DV887 (Andor Technologies) is shown in the inset of Fig. 3, right (obtained with an argon ion laser pump).

Figure 3 shows the schematics of the experimental setup with a 405-nm diode laser. The 10-nm bandwidth interference filters are used for selection of a definite wavelength of

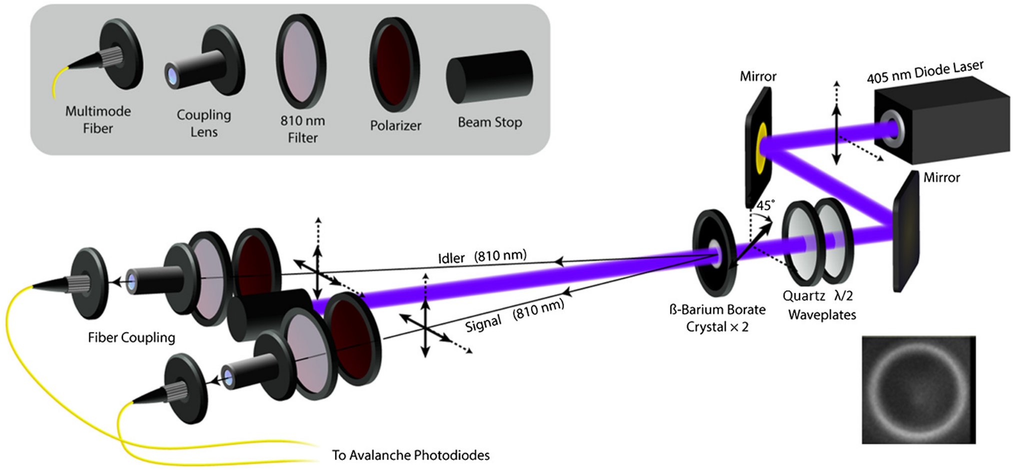


Fig. 3 Schematics of an experimental setup of polarization entangled photons with two BBO crystals and a diode laser. Inset at the right shows one of SPDC cones (in a plane perpendicular to beam propagation direction) under argon ion laser excitation recorded by an EM-CCD camera. A 10-nm bandwidth interference filter was used to select 2λ wavelength and to reject the pump. A quartz plate was used to compensate the phase difference Δ (prepared by R. Lopez-Rioz).

SPDC photons (810 nm in this setup) propagating at a definite cone angle. Two single-photon counting avalanche photodiode modules (APDs) AQR-14 (Perkin Elmer) are used as detectors A and B. A collection system to APDs (microscope objectives and optical fibers) is located at the opposite ends of a downconverted cone diameter.

Using polarizers rotated to angles α and β in the signal and idler paths, respectively, the polarization correlation of the downconverted photons is measured. The response from two APDs is processed with a counter-timer computer card that allows the recording of signals from each APD (singles) and their simultaneous response (coincidences).

The probability P of coincidence detection for the case of 45-deg incident polarization on the BBO crystal set and $\Delta = 0$ depends only on the relative polarizer angle β-α:

$$P(\alpha, \beta) = \frac{1}{2}\cos^2(\beta - \alpha). \tag{3}$$

However, APD singles count does not depend on polarizers' rotation angles. The correlations described by Eq. (3) can be recorded only in coincidence count using a counter-timer board (National Instruments 6602 with a time window of 26 ns).

The pictures of two entanglement setups using the same detectors with Toptica Photonics diode (405 nm, 120 mW maximum) and Spectra-Physics argon ion (363.8 nm, 100 mW maximum, single-longitudinal mode) lasers are shown in Fig. 4(a). Usually during the class, only 25- to 30-mW power is used in both lasers. Two fiber-connected APDs are used in both setups. BBO type I crystals were cut at different angles optimized for each wavelength (Newlight Photonics, Inc.). For a 363.8-nm signal wavelength, the optic axis cut angle was $\theta = 32.63$ deg with crystals dimensions $5 \times 5 \times 0.6\ \text{mm}^3$, whereas for a 405-nm wavelength, $\theta = 29$ deg with crystal dimensions $5 \times 5 \times 0.6\ \text{mm}^3$. The angle between signal and idler photons with 2λ wavelength was ~6 deg in both cases. Figure 4(b) shows a collection system, APDs, and two linear polarizers mounted on rotating mounts. A crystal set mount is shown in Fig. 4(c).

Figure 5 shows the experimental polarization correlation for fixed angles of a polarizer A $\alpha = 45$ deg and 135 deg and the rotation of polarizer B only (an argon ion laser setup). The experimental data are consistent with relation (3): coincidence counts reached the maximum when polarizers were parallel ($\alpha = \beta$). Further, fringe visibility $\text{Vis} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$ of 0.9 was observed (greater than 0.71), thereby indicating a possibility of entanglement.

To further explore entanglement in the system, Bell's inequality should be violated. The CHSH Bell inequality[56] constrains the degree of polarization correlation under measurements at different polarizer angles. The proof involves two measures of correlations, $E(\alpha, \beta)$ and S

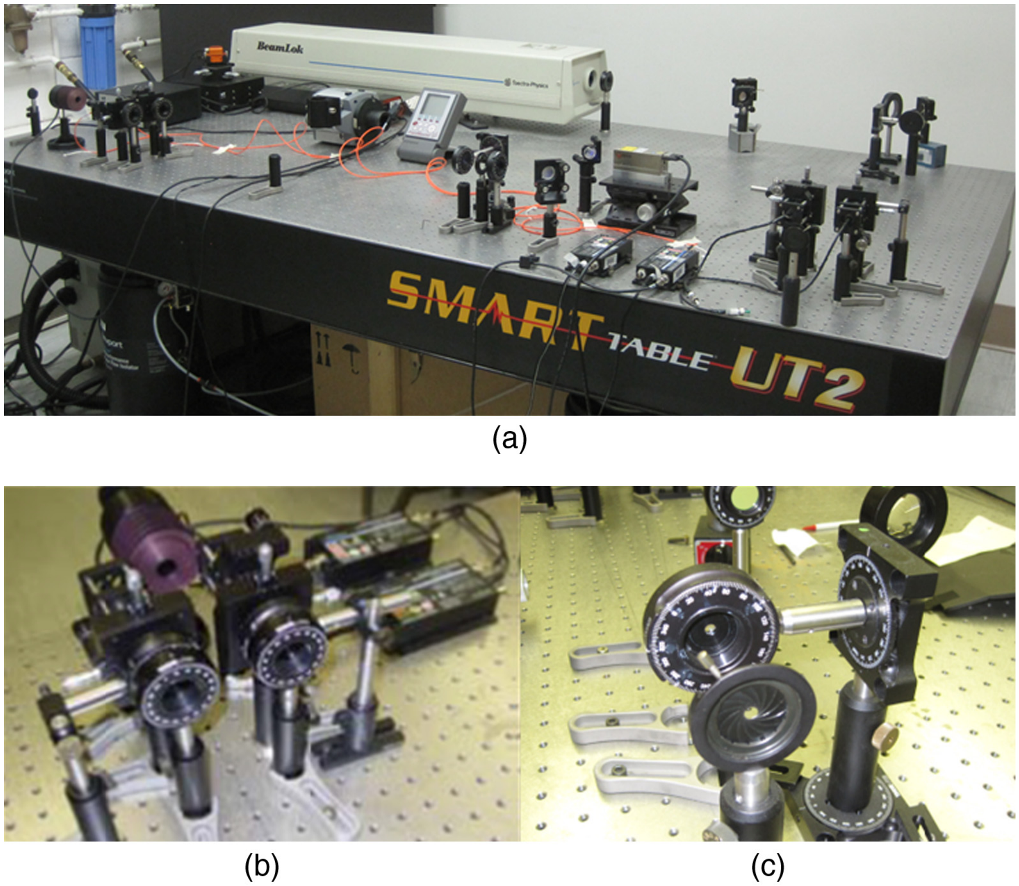


Fig. 4 (a) Two entanglement setups for the teaching labs of the Institute of Optics, UR. (b) Collection system with a three-dimensional (3-D) adjustable mount with two polarizers and APD detectors. (c) BBO crystal set with a 3-D rotation mounting (an iris diaphragm serves for alignment).

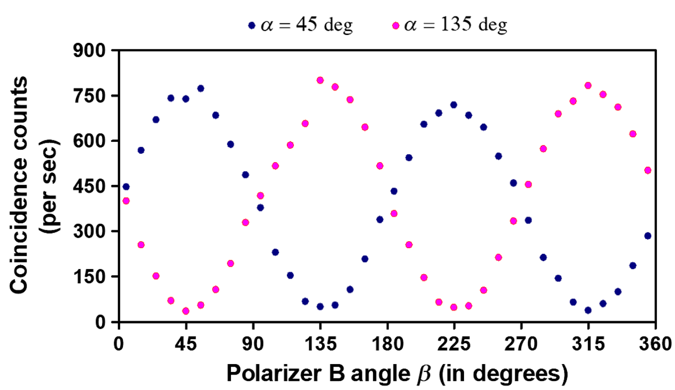


Fig. 5 Polarization correlations: dependence of coincidence count on relative polarizer angle.

(P_{VV} and P_{HH} are probabilities of both photons to have vertical or horizontal polarizations, whereas P_{VH} and P_{HV} are probabilities of photons to have opposite polarizations, respectively), $N(\alpha, \beta)$ are the measured coincidence counts at polarizers angles α and β. Violation of CHSH Bell's inequality occurs if the modulus of $S > 2$. In addition, S does not have a clear physical meaning.

$$E(\alpha, \beta) = P_{VV}(\alpha, \beta) + P_{HH}(\alpha, \beta) - P_{VH}(\alpha, \beta) - P_{HV}(\alpha, \beta), \tag{4}$$

Table 1 Data of 16 measurements of coincidence counts at 16 combinations of polarizers' angles with maximum value of S. In this case, $S = 2.76 \pm 0.06$. At some angles, the value of modulus of S can be less than 2, even in the case of entanglement. A 405 nm diode laser setup.

	$\beta = -22.5$ deg	$\beta' = 22.5$ deg	$\beta_\perp = 67.5$ deg	$\beta'_\perp = 112.5$ deg
$\alpha = -45$ deg	179	34	34	173
$\alpha' = 0$ deg	163	180	43	19
$\alpha_\perp = 45$ deg	12	161	239	58
$\alpha'_\perp = 90$ deg	53	25	207	226

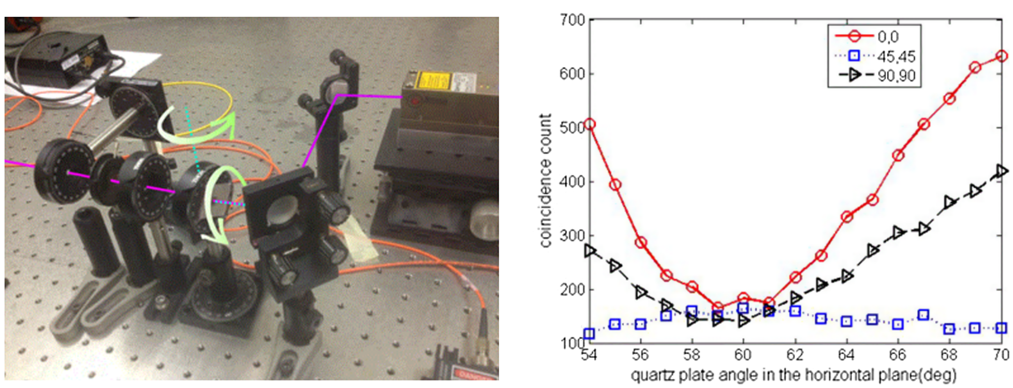
$$E(\alpha,\beta) = \frac{N(\alpha,\beta) + N(\alpha_\perp,\beta_\perp) - N(\alpha,\beta_\perp) - N(\alpha_\perp,\beta)}{N(\alpha,\beta) + N(\alpha_\perp,\beta_\perp) + N(\alpha,\beta_\perp) + N(\alpha_\perp,\beta)}, \tag{5}$$

$$S = E(\alpha,\beta) - E(\alpha,\beta') + E(\alpha',\beta) + E(\alpha',\beta'). \tag{6}$$

The above calculation of S requires a total of 16 coincidence measurements (N) at definite polarization angles α and β. Table 1 presents one example from the Fall 2021 OPT 453 class with the experimental net coincidence count data after optimization of phase difference Δ. The net coincidence counts are calculated as $N_{\text{net}} = N_{\text{avg}} - N_{\text{ac}}$, where N_{av} is the average coincidence count and $N_{\text{ac}} = \frac{N_A N_B \tau}{t}$ is accidental coincidence count [N_A and N_B are single count rates on detectors A and B, τ is a counter-timer time window, and t is the accumulation time ($t = 1$ s for Table 1 data)].

Polarization angles are selected with a maximum value of S from CHSH Bell's inequality to violate it.[56] At many other angles, the modulus of S is <2 from a CHSH theory. Usually, in our experiments, $S_{\max}$ varies between 2.2 and 2.76 (greater than 2) at different levels of alignment ($S_{\max} = \text{Vis}2\sqrt{2}$). For Table 1, data S take on the calculated value of $S = 2.76 \pm 0.06$.

To compensate for the phase difference Δ [see Eq. (2)] between downconverted photons with vertical and horizontal polarizations (one passes through two BBO crystals; the other, through only one crystal), an X-cut quartz plate (0.5- to 1.0-mm thickness range) rotated both in horizontal and vertical planes was placed into the beam entering the crystals [see Fig. 6(a)]. Three coincidence count curves should be plotted, corresponding to the (α,β) values of (0 deg, 0 deg), (45 deg, 45 deg), and (90 deg, 90 deg) at different angles of rotation of a quartz plate. The coincidence counts at the three polarizer settings undergo drastic changes as the quartz plate rotates either around horizontal or vertical axes [see Fig. 6(b)]. The optimal position of a quartz plate is when the coincidence counts for all settings is equal (intersection of the curves).



(a) (b)

Fig. 6 (a) A quartz-plate mount with a two-dimensional-rotation (prepared by A. Ariyawansa). (b) Coincidence count changes as the quartz plate is rotated around the vertical axis. The angle of rotation around the horizontal axis is fixed (from students' report; a 408 nm diode laser setup).

For data acquisition (both singles and coincidences), two LabVIEW programs were used: in case of Bell's inequality with standard deviation and for building $\sim\cos^2(\beta\text{-}\alpha)$ curves. Excel programs calculate values of S with standard deviation and build the plots from coincidence count data, considering accidental coincidences.

This lab was divided into four 1.5 to 3.0 h lab sessions (see Fig. 2 for details).

2.2 *Lab. 2. Single-Photon Interference (Young's Double Slit and Mach–Zehnder Interferometers)*

This is a favorite lab for most of the QNOL students. The undergraduate students learn that the first experiment on a feeble light interference was obtained in 1909 by Sir G. I. Taylor[65] when he was an undergraduate student. Students also learn that Young's double slit experiment had a tremendous influence on the history of science, and it continues to inspire and direct modern researchers to use it and its modifications (e.g., Mach–Zehnder interferometer) to probe new areas of physics.[66]

In this lab, wave-particle duality using an example of single photons is demonstrated (Bohr's complementarity that simultaneous observation of wave and particle behavior is prohibited by the position–momentum uncertainty relation). For this lab, an attenuated laser beam (a Poissonian light source) is a good approximation for a source of single photons, although photon antibunching (separation of all photons in time) cannot be achieved in such a source. Interference between single photons is observed in both Young's double slit and Mach–Zehnder interferometers. In a Mach–Zehnder interferometer experiment with a polarizing beamsplitter at its input, the effect of "which path" information is shown, as an inference pattern can only be acquired when that information (known linear polarization of single photons in each interferometer arm) is hidden using a 45-deg linear polarizer (quantum eraser) at an interferometer output. This laboratory provides a visual demonstration of the appearance and disappearance of interference fringes, both at laser light power, visible at room light, and single-photon levels, by carefully destroying and restoring "which-path" information using a quantum eraser in a Mach–Zehnder interferometer (further details in Refs. 21, 25–28, and 33).

Measurements are made using a He–Ne laser beam, attenuated to the single-photon level with neutral density filters. In the QNOL classes, an EM-CCD camera iXon by Andor Technologies cooled to −65°C and sensitive to single photons is used. It is also employed with MCC students' groups and freshman research projects. However, in classes with 40 to 50 students (a required OPT 204 class Sources and Detectors), a conventional CMOS Basler acA1920-40um USB 3.0 camera with a Sony IMX249 CMOS sensor is utilized for recording interference fringes from faint laser light attenuated for a single photon level (∼1 photon per meter) but at a longer exposure time (∼10 s). Students also learn from the lecture that the human eye is sensitive to a few photons,[67,68] and even the Nobel Prize in Physics (1958) was awarded for observation by Cherenkov of a feeble cone of Vavilov-Cherenkov radiation (1934) after accommodation of his eyes to darkness.[67]

Figure 7 shows the schematics of two experiments of this lab: Young's double slit [Fig. 7(a)] and Mach–Zehnder interferometers [Fig. 7(b)]. Initially, 10-μm width slits with a 90-μm slit separation fabricated via lithographic deposition of a metal on a glass substrate were used. This type of a double slit provides interference pattern because of interference of light diffracted by the slit and reflected light from reflective surface of a substrate. In this case, a fine structure appears in the interference maxima of a double slit interference [inset in Fig. 7(a)]. Although it does not influence a wave-particle duality, recently, a transition to the double slit with opening in the air was made (a 40-μm width with a 125-μm slit separation, PASCO high precision diffraction slits).

Figure 8 shows the experimental setup of the Young's double slit single-photon experiment, with an EM-CCD camera as a detector (a), a Mach–Zehnder interferometer (b), and a quantum eraser (c). Further, Fig. 9(a) shows the results of a quantum eraser experiment (solid line) on dependence of fringe visibility at the Mach–Zehnder interferometer output on the angle θ_p of a linear polarizer (quantum eraser). The calculated dependence of fringe visibility using the Malus law is shown in the same figure (dashed line). EM-CCD images with maximum fringe visibility of the interference pattern at the single-photon level with a 200-ms single exposure time (top)

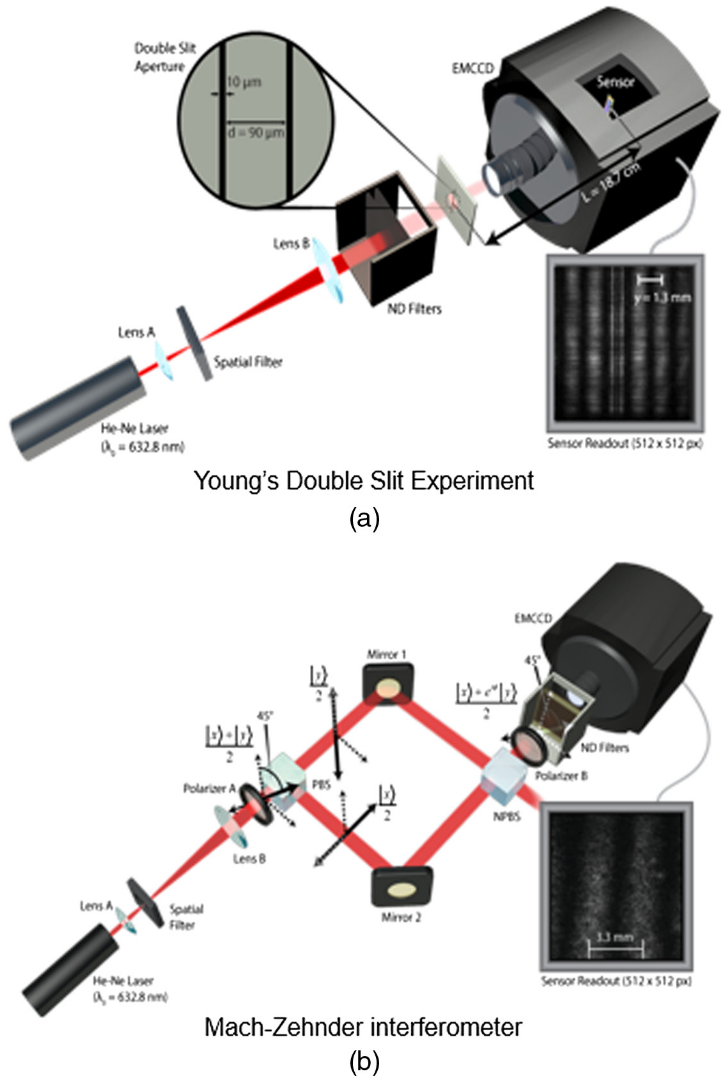


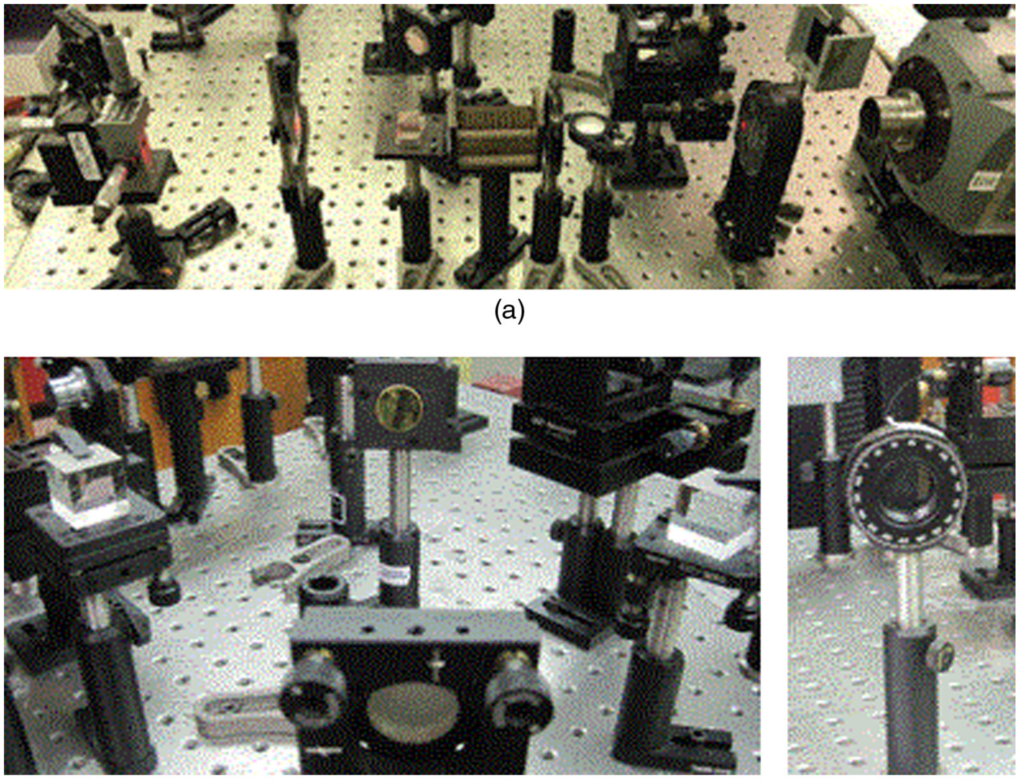
Fig. 7 (a) Setup of a single photon Young's double slit experiment. ND, neutral density filters; EMCCD, electron multiplying CCD camera; He–Ne, helium–neon laser. The inset at the right shows double-slit interference with a "lithographic" slit. A fine structure is seen inside the maxima (see explanation in the text) (prepared by R. Lopez-Rios). (b) Setup for a Mach–Zehnder interferometer. PBS, polarizing beam splitter; NPBS, nonpolarizing beam splitter. The polarization vector is shown at each point of change in the system state (prepared by R. Lopez-Rios).

and with accumulation of 50 images with a 200-ms exposure time each are shown in Fig. 9(b). The third part of the lab (including a 3-h version) is the alignment of a Mach–Zehnder interferometer. A TA destroys the alignment by removing two mirror mounts from the post holders. Thereafter, students are required to realign the interferometer.

In QNOL classes, this lab comprises two 1.5- to 3.0-h sessions (see Fig. 2 for details).

2.3 *Lab 3. Single-Photon Source I: Confocal Microscope Imaging of Single-Emitter Fluorescence*

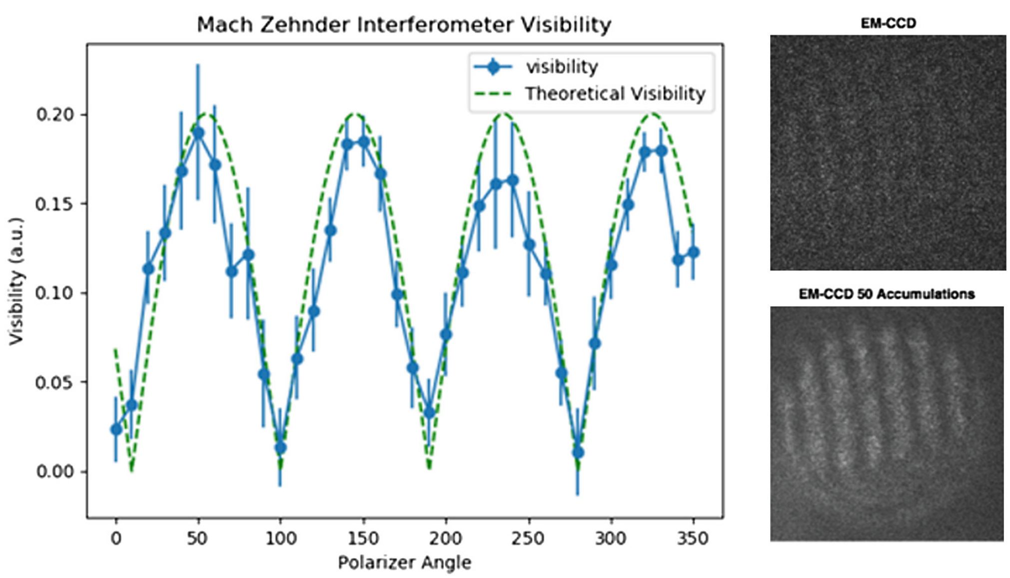
The offered QNOL courses enable students to engage in a real research environment, working on state-of-the-art, fragile, and expensive equipment used in modern quantum-optics research worldwide and that they had already used in labs 1 and 2. Every student understands the cost of each piece of equipment. In addition, in labs 3 and 4, class time was reserved for addressing "real" research questions on actual research samples or, time permitting, students prepared their



(a)

(b) (c)

Fig. 8 Parts of experimental setup for single-photon interference lab (a He–Ne laser is not shown). (a) A Young's double slit interferometer with an EM-CCD used as a detector. (b) A Mach–Zehnder interferometer; (c) a quantum eraser.



(a) (b)

Fig. 9 (a) Dependence of fringe visibility of accumulated images at the output of a Mach–Zehnder interferometer on a linear polarizer (quantum eraser) angle θ_p. Theoretical curve Vis $= |\sin 2\theta_p|$ is shown on the same plot. A zero on a mount angle scale of a linear polarizer had a small shift relative to a polarizer axis. Maximum fringe visibility should be at a 45-deg angle (prepared by A. Ariyawansa). (b) EM-CCD images of the interference pattern (maximum fringe visibility angle) at a single photon level with a 200-ms single exposure time (top) and with accumulation of 50 images with a 200-ms exposure time (bottom).

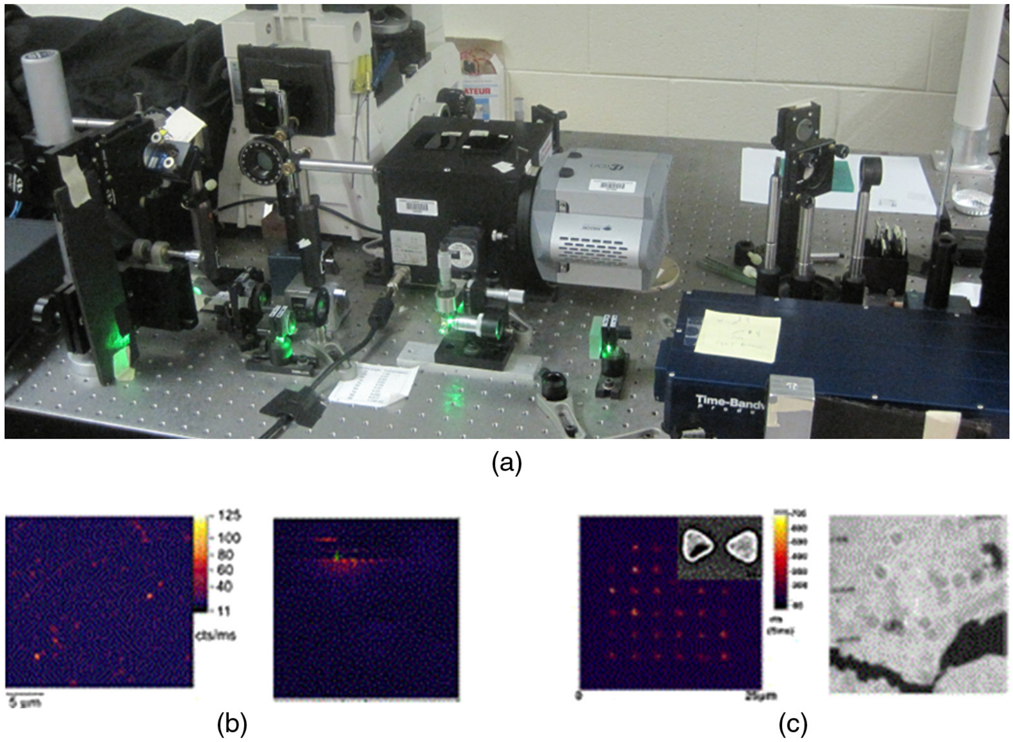


Fig. 10 (a) Confocal fluorescence microscope with a Hanbury Brown and Twiss interferometer (covered by a black tissue) and a spectrometer with an EM-CCD camera. (b) (Two micrographs): Confocal microscope imaging of single NV-centers fluorescence in 40-nm and 20-nm size nanodiamonds. Right figure of two shows blinking in fluorescence (horizontal stripes) of a single color center in a 20-nm-nanodiamond (2×2 μm raster scan). (c) (Two images): Confocal microscope micrograph of gold photoluminescence from a bowtie nanoantenna array. Inset shows the bowtie shape of nanoantenna (SEM micrograph by Z. Shi). Right figure of two shows a wide-field sample view recorded by a CCD-camera showing a position of different nanoantenna arrays (numbers 30 to 50 nm are the value of gaps of nanoantennas located close to these numbers).

own samples with single emitters that have never been investigated prior to them. Thus, this intentional blurring of the dividing line between "education" and "research" strongly increases student interest.

Labs 3 and 4 serve to understanding SPS (antibunched),[49,69–71] a key hardware for long-distance quantum communication. To create single photons, a laser beam is focused on a single emitter that emits a single photon at a time. Single colloidal, semiconductor, nanocrystal quantum dots, and color centers in nanodiamonds were used as single emitters in these labs. Figure 10(a) shows the experimental setup of labs 3 and 4. A confocal fluorescence microscope with excitation by laser light of different wavelengths was used in a lab 3 for imaging and spectral evaluation of single emitter fluorescence. Figures 10(b) and 10(c) show confocal-microscope raster scan fluorescence images of NV (nitrogen vacancy)-color-center nanodiamonds with diameters of 40 and 20 nm (left two micrographs) and photoluminescence of a Au bowtie nanoantenna array (inset shows nanoantenna shape with 75-nm arms and 30 to 60 nm gaps) (right micrograph). The fourth image in Fig. 10(c), right image, shows a wide-field view of a sample area in a white light. Numbers identify the positions of nanoantenna arrays with different gaps. Consequently, students learned how to find a specific array for imaging.

2.4 *Lab. 4. Single-Photon Source II: Hanbury Brown and Twiss Setup. Fluorescence Antibunching*

To prove the single-photon nature of single-emitter fluorescence (antibunching), students measure time intervals between consecutive photons in lab 4. Antibunching was first obtained at the

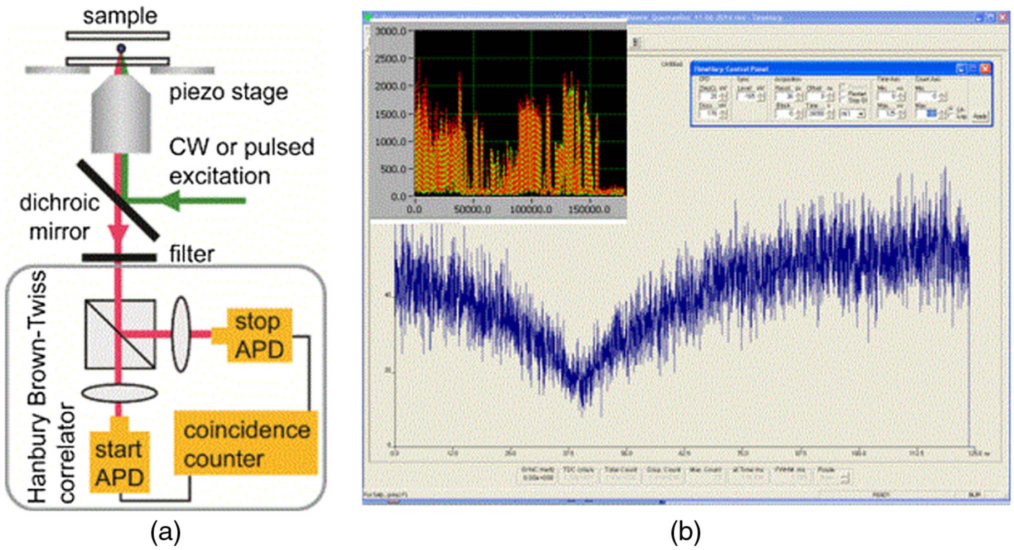


Fig. 11 (a) Schematics of experimental setup with a confocal fluorescence microscope and a Hanbury Brown and Twiss correlator (prepared by L. Bissell). (b) Raw data histogram of interphoton times with a dip at zero interphoton time indicating photon antibunching. Fluorescence of NQD inside a gap of a bowtie nanoantenna was studied. Inset shows a time trace of this quantum dot fluorescence.

UR in 1977 by Mandel, Kimble, and Dagenais.[69] Further details can be found in Ref. 70, book,[71] and review.[49]

For antibunching, no photons should appear at zero interphoton time. For such measurements, a Hanbury Brown and Twiss correlator[72] is used [Fig. 11(a)]. It consists of a beamsplitter and two single-photon counting APDs. Electronic readout during students' measurements consists of a time-correlated, single-photon-counting PCI card with start and stop inputs connected to the APDs. This card (Time Harp 200, Picoquant) in conjunction with software allows to build a histogram of interphoton times. Subsequently, in the case of antibunching, a dip appears at zero interphoton time. In the lecture, a history of discovery of a Hanbury Brown and Twiss effect was discussed.[73]

Figure 11(b) shows a user interface of the program for building the histogram with a dip at a zero interphoton time indicating antibunching. In class, CdSeTe colloidal-nanocrystal quantum dots (NQD), each localized at a gold, bowtie nanoantenna, served as a single emitters. These 2015 QNOL class results were reported at the 2016 Frontiers in Optics conference.[74] While collecting the histogram data, students recorded the time traces of intermittent blinking by single emitters (NQD) on a second platform, as shown in Fig. 11(b) (inset, the blinking of a single NQD).

Labs 3 and 4 are connected to each other and they consist of total five ~1.5 to 3-h lab sessions (see Fig. 2 for details).

Following the QNOL class, students frequently continue participating in ongoing efforts on a SPS setup, either through independent studies or within the framework of senior projects. During final publication of results (of experiments started in the QNOL class), they become coauthors.[74,75]

3 Using QNOL Facility for Required UR Classes

3.1 *Research Projects: From Freshmen to Graduate Students*

Starting from 2009, 6- to 9-h quantum optics labs were introduced into the freshman-level course OPT 101 "Introduction to Optics" (W. Knox and T. Brown) as class research projects. TAs (PhD students) assisted in these projects. In 2010, 16 freshmen were divided into three groups for projects covering all QNOL labs: entanglement and Bell's inequalities, single photon interference, and SPS (antibunched). At each semester end, freshmen present their posters during a special session attended by other students and faculty of the Institute of Optics. Further, the entanglement lab became popular among Department of Physics and Astronomy seniors of the "Advanced Experimental Techniques" class (PHY 243W). In addition, graduate "quantum" projects of the Optical Laboratory (OPT 456) are also based on the QNOL facility. A master's student from SUNY Geneseo completed a thesis on entanglement using this facility.

3.2 *Introduction of Quantum Mini-Labs into Required UR Lecture and Lab Classes*

Short, 3-h mini-labs were introduced into several other UR classes. For instance, in a required lecture class "Quantum Mechanics for Optical Devices" (OPT 223), taught by C. Stroud for juniors and seniors, 3-h versions of entanglement and single-photon interference labs of QNOL were introduced. Consequently, the success of this approach further facilitated the inclusion of two 3-h quantum labs to specifically created required labs and lecture class "Sources and Detectors" (OPT 204) for juniors and seniors taught by the author. OPT 204 is a complimentary class to two required lecture classes, with one being "quantum" OPT 223. In the OPT 204 class, a single-photon interference lab with a conventional CMOS camera as a detector is included along with a lab on photon counting statistics, developed by N. Vamivakas for this class from the experiment described in Ref. 30. In this experiment, students familiarize themselves with photon counting by measuring a Poissonian photon statistics from a laser light attenuated to a single-photon level and Bose–Einstein statistics from a pseudothermal source created using a rotating ground glass in a laser beam. Figures 12(a) and 12(b) show the experimental setup, the LabView software user interface with photon statistics data in time bins shorter and longer than the

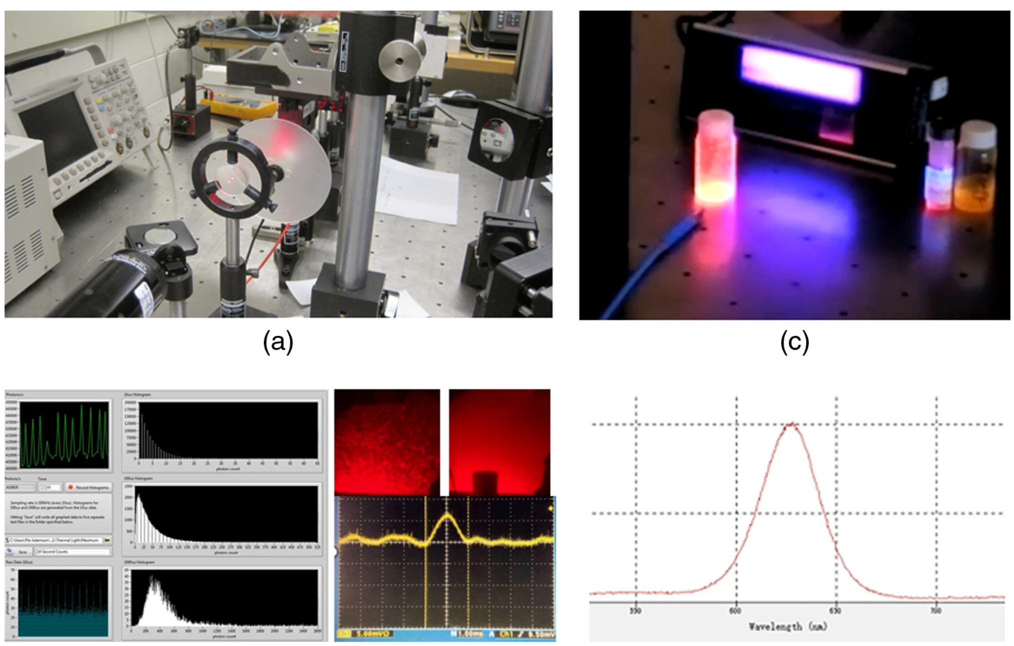


Fig. 12 Two OPT 204 class quantum mini-labs (not included to QNOL classes). (a): Setup of a 3-h mini-lab session on a pseudothermal source with a rotating ground glass. (b) User interface of a LabView software showing photon statistics changes for data collected with different time bins [less or longer than a coherence time (see a provided oscillogram)]. Two laser beam cross sections show speckles at the output of a still ground glass (Poisson statistics) and speckles disappearance with a ground glass rotation. (c) Setup of a 15-min mini-lab session on using Schrödinger equation for calculation of sizes of NQDs from spectral measurements. Vials with NQD solutions fluoresce under UV source illumination. A spectrometer fiber input is seen at the left. (d) Fluorescence spectrum from a quantum dot solution recorded by a fiber-optics spectrometer.

coherence time, the oscillogram determining the coherence time, and the laser beam cross-sections at the output of both still and rotating ground glass.

One more quantum, 15-min mini-lab on using Schrödinger equation for calculation of sizes of NQDs from spectral measurements is included into this class [see picture and spectrum in Figs. 12(c) and 12(d)]. This lab is discussed in detail in Sec. 4.1 of our paper[41] of this journal issue. In addition to lab lectures discussing the experiments and equipment, a special lecture-workshop on nonclassical light sources is included in this class. Consequently, both the written and oral final exam ("Big" quiz) of all lab content contain questions on antibunching and entanglement discussed in this lecture.

4 Participation by the Local Monroe Community College and Other Colleges and Universities

4.1 *Monroe Community College*

From 2009 to 2015, MCC students (both from STEM majors and nonmajors) participated in labs at the UR QNOL facility. MCC students participated in 3-h sturdy mini-labs on (1) entanglement and Bell's inequalities and (2) single-photon interference with a single-photon-counting, EM-CCD camera. MCC professor P. D'Alessandris was instructed in the use of the EM-CCD camera, to teach his MCC students the single-photon interference lab at the UR. The author of this paper taught MCC students the entanglement and Bell's-inequality lab. Within this collaboration supported by three NSF grants, lab manuals were specifically rewritten for MCC students.

4.2 *Rochester Institute of Technology*

Rochester Institute of Technology (RIT) was a collaborator in one of the NSF-supported projects on developing teaching experiments on photon quantum mechanics using photon counting instrumentation. During fall 2009, Prof. R. Jodoin from RIT spent his sabbatical year in UR teaching labs. Later, RIT established its own quantum-optics teaching lab, strengthening the Upstate New York future-optics roots. Further, Prof. S. Preble established a quantum-optics teaching lab on entanglement, extending the UR experience.

4.3 *Advanced Laboratory Physics Association Immersion Program*

In August 2011, UR participated in the Immersion Program of the Advanced Laboratory Physics Association (ALPhA).[76] Six visitors from different universities were hosted for 3 days and familiarized with UR lab-course experience in photon quantum mechanics. Professor M. Braunstein (Central Washington University), Prof. J. Buchholz (California Baptist University and University of California, Riverside), Prof. T. Perera (Illinois Wesleyan University), Prof. M.C. Sullivan (Ithaca College), Prof. W.F Smith (Haverford College), and D. Dominguez (graduate student responsible for teaching Labs, Texas Tech University) participated in all four labs of the QNOL class.

4.4 *Adelphi University Students' Visit to the University of Rochester*

For 2 days (October, 2012), five students from Adelphi University and their professor S. Bentley participated in all four labs at the UR QNOL facility. They also prepared one-dimensional-photonics bandgap materials for SPS applications based on cholesteric liquid crystals.[77]

4.5 *Dissemination of Results to Other Universities*

A graduate student supervised by Prof. P. Verma (University of Oklahoma, Tulsa) was trained at the Rochester lab facility in October, 2010. Earlier (in September of 2010), the author was invited to Tulsa to share the UR experience on quantum-optics labs with this host university. Students from different universities visited UR facilities with their professors for lectures-demonstrations, for instance, from SUNY Alfred University (spring 2012, Prof. S.K. Sundaram) and Colgate University (Prof. E. Galvez). Further, in June, 2013, ITMO University (Saint Petersburg, Russia) included a lecture on the UR QNOL facility at the Young Scientists Workshop.

5 Assessment Methods, Learning Outcomes, and Students' Attitude Toward Careers in Quantum Information

How best to educate future quantum engineers?[78] Assessments of students' performance and their understanding associated with the science laboratory is an integral part of the laboratory work for professors and students.[79] Assessment methods of advanced lab courses have been discussed in the literature; for example, Ref. 80. Assessment of the outcomes of completion of the specific lab courses by students can reveal the demonstrative abilities of students in terms of knowledge and skills. We maintained three learning measurable outcomes: (a) students are able to demonstrate knowledge of the concepts of entanglement, antibunching, quantum superposition and interference, wave-particle duality, single photons (assessment methods: quizzes before each lab, exams, essays, and students presentations); (b) students can demonstrate mastery in photon-counting instrumentation [assessment methods: lab reports, lab journals (see also Ref. 81)]; (c) students are involved in research, combining research, and education (assessment methods: reports, senior theses, students presentations).

Some our methods for evaluation of students' knowledge of different classes were developed through quizzes and exams that involved the participation of an external evaluator (Prof. Zawicki, Buffalo State College). Herein, we present the evaluation results of knowledge gained by students during one academic year of NSF support by Zawicki from our collected data (Sec. 5.1), and our recent results on the QNOL classes and OPT 204 class with quantum mini-labs (Sec. 5.2).

5.1 *Classes with Quantum Optics Experiments in Academic Year 2010–2011*

In the academic year 2010–2011, 52 students, who were mostly undergraduates, either completed course-based laboratory activities or conducted research using the QNOL facility. Students from the UR, MCC, and SUNY Geneseo participated in various activities, as shown in Fig. 13. One graduate student utilized of the QNOL facility to complete their master's thesis. Student participants during the fall 2010 and spring 2011 semesters were surveyed with respect to their content knowledge as well as their impressions regarding the activities and science in general. The survey results are presented below.

Course/Campus	Students (N)	Experiences
Fall 2010		
OPT253	6	Quantum Optics and Quantum Information Laboratory. Students met in three-hour sessions, twice per week (90 Contact Hours).
OPT101	16	Freshman Research Project. Students completed 12-hour projects. The students self-selected for participation in one of three projects under the direction of graduate students.[1]
Spring 2011		
OPT223	12	Quantum Mechanics of Optical Materials and Devices. Students completed a lab activity integrated into the course curriculum – Lab 1. Entanglement and Bell's Inequality and Lab 2. Single Photon Interference
PHY262 (MCC)	17	Modern Physics Course. Students from Monroe Community College participated in two lab activities – Entanglement and Bell's Inequalities, and Single Photon Interference.
SUNY Geneseo	1	A master's student from SUNY Geneseo completed a thesis on entanglement using the QNOL facility at the University of Rochester.

Fig. 13 Students' participation in quantum optics experiments in academic year 2010-2011 (by course and campus). [1]A total of 40 students enrolled in this campus-wide program (OPT 101). 16/40 students (40% of the OPT 101 course enrollment) opted to participate in the "quantum" research projects (prepared by J. Zawicki).

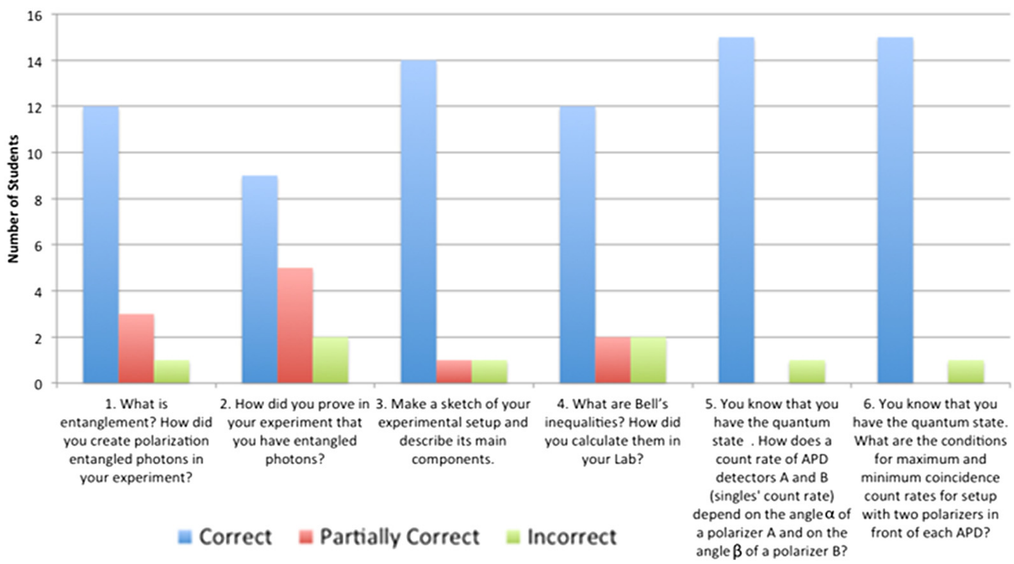


Fig. 14 Histogram of students from the Monroe Community College class answering correctly, partially, or incorrectly to several questions of the entanglement lab (prepared by J. Zawicki).

Student participants in PHY 262, a course offered through MCC, were presented with six questions related to a laboratory activity addressing entanglement and Bell's inequalities. The student scores for each lab question are shown in Fig. 14 (numbers of students answering items correctly, partially correctly, or incorrectly). The individual item difficulties ranged from 0.72 to 0.94; the most difficult items were #1 (0.84), #2 (0.72), and #4 (0.81). Students faced the greatest difficulty in explaining how their experimental data proved the existence of entangled photons (question #2). Students had some difficulty providing an explanation of both entanglement (question #1) and Bell's inequalities (question #4). The class attained mastery on the remaining items.

Students in the OPT 101 freshman class completed prelab, lab, and postlab questions. The grades for five students are shown in Fig. 15. Student gains from prelab through postlab

Student Assignments					
Pre-lab Questions					
Student	***Correct***	***P. Incorrect***	***P. Correct***	***Incorrect***	***Difficulty***
Student #1	4	1	4	1	0.60
Student #2	-	-	-	-	-
Student #3	4	3	2	1	0.67
Student #4	-	-	-	-	-
Student #5	-	-	-	-	-
Lab Questions					
Student	***Correct***	***P. Incorrect***	***P. Correct***	***Incorrect***	***Difficulty***
Student #1	7	1	2	0	0.83
Student #2	6	3	1	0	0.83
Student #3	6	3	1	0	0.83
Student #4	6	2	1	1	0.77
Student #5	4	4	0	2	0.67
Post-lab Questions					
Student	***Correct***	***P. Incorrect***	***P. Correct***	***Incorrect***	***Difficulty***
Student #1	8	2	0	0	0.93
Student #2	7	3	0	0	0.90
Student #3	7	2	1	0	0.87
Student #4	6	4	0	0	0.87
Student #5	9	1	0	0	0.97

Fig. 15 Students' scores in lab assignments of the OPT 101 class (prepared by J. Zawicki).

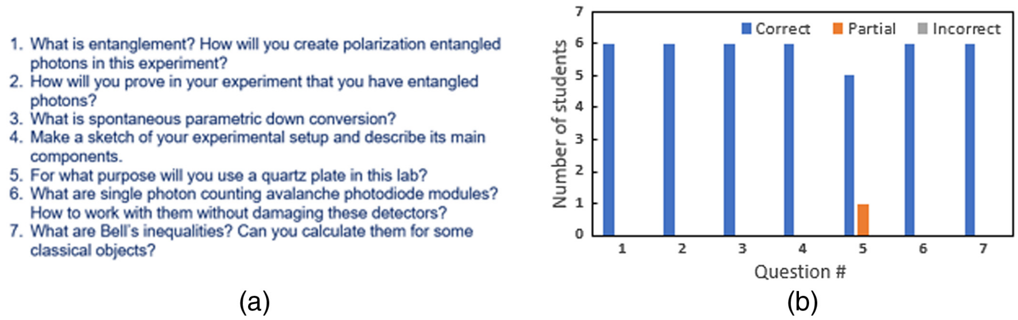


Fig. 16 (a) Entanglement lab quiz questions for OPT 223 students. (b) Histogram of a number of students of OPT 223 that answered the entanglement quiz questions correctly and partially.

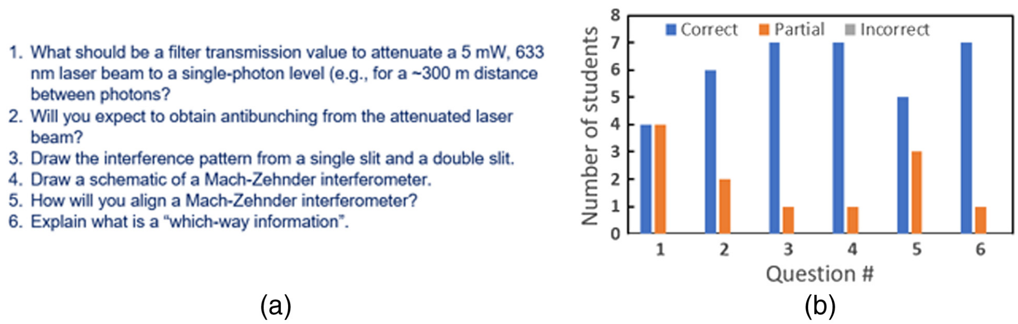


Fig. 17 (a) Single-photon interference lab quiz questions for OPT 223 students. (b) Histogram of a number of students of OPT 223 that answered correctly and partially to single-photon interference quiz questions.

responses are substantial. Students demonstrated substantial gains between their prelab and their postlab responses. In this course, the students created PowerPoint presentations of their research on the QNOL facility over the course of a semester, wherein they showed remarkable progress. Importance of the OPT 101 course is that it teaches students, who are in their first semester after completing high school, to think and act "like a physicist."[82,83]

Students in OPT 223 with two 3-h mini-labs completed two lab reports; student scores on the several questions for each lab [Figs. 16(a) and 17(a)] addressed in each report are shown in Figs. 16(b) and 17(b). The data support the conclusion that the students were able to fully respond to the questions posed in lab #1 and were largely able to provide mostly correct answers to the questions posed in lab #2.

Figure 18 shows the evaluation results of students learning using a quiz consisting of nine questions for the students in the Fall 2010 OPT 253 course. Questions 1 and 6 were the most difficult items on this quiz. The items contained in the survey had difficulty levels above mastery (85%), except for two items (2 and 7). The data support the conclusion that the students completing these activities understood these activities well.

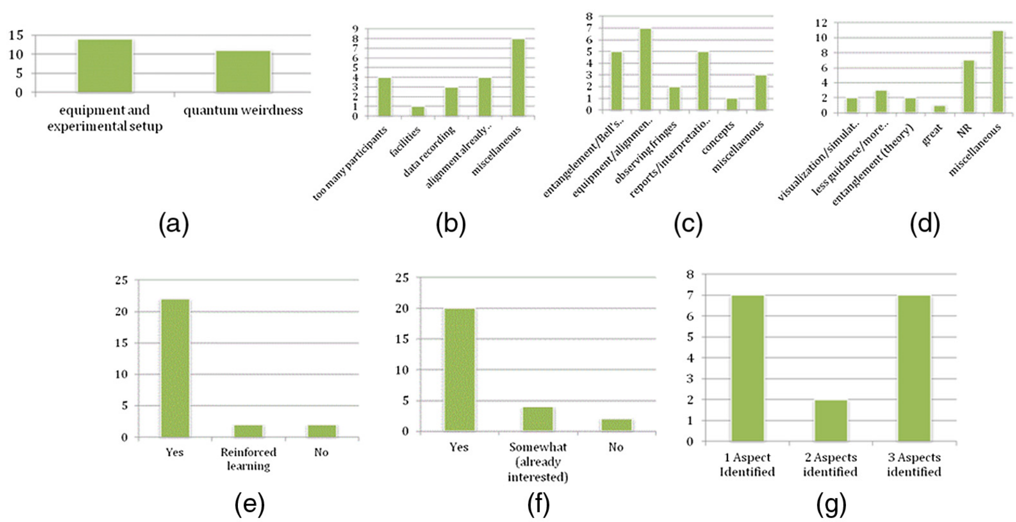
Both the undergraduate students from the UR (OPT 223) and MCC (PHY 262) completed surveys regarding various aspects of the lab activities and their understanding of the nature of science.

Figure 19(a) provides data indicating that 14 students were most intrigued by the equipment (setup, use, alignment), among which, ∼11 of them were most intrigued by the idea of quantum entanglement or quantum weirdness at some level. On the "equipment" side, typical student statements included: "actually getting to conduct experiments with very advanced equipment," and "experience with high-quality lasers and detectors." On the quantum side, comments such as "The fact that an action in the present can change something (which path the photon took) in the past" are indicative of students' ability to grapple with these complex quantum issues.

Figure 19(b) provides an overview of what students considered to be the least important aspects of these activities. In general, students would like to have smaller lab groups—they felt

Item	Correct	Partially Correct	Incorrect	Difficulty
1. Explain complementarity (wave-particle duality) of photons in your experiment.	9	4	4	65%
2. Draw the interference pattern from a single- and double-slit.	13	0	4	76%
3. Sketch (on the figure below) the intensity pattern on the screen you would see if one slit was blocked.	16	0	1	94%
4. Sketch…if both slits were open. Sketch… of bullets if one slit was blocked.	16	0	1	94%
5. Sketch…the accumulation pattern of bullets…if both the slits were open.	15	0	2	88%
6. If light is nothing but particles, why doesn't a stream of bullets give rise to an interference pattern similar to that of photons.	8	6	3	65%
7. Draw the schematics of a Mach-Zehnder interferometer.	13	1	3	79%
8. Will you observe single-photon interference at the output of a M-Z interferometer if you will know in which arm of this interferometer photons can be horizontally and vertically polarized?	14	3	0	91%
9. How many photon/s with a wavelength of 633 nm do you have at laser power 1 mW?	14	3	0	91%

Fig. 18 OPT 253 students' knowledge analysis of a single-photon interference lab (prepared by J. Zawicki).



Student responses to survey items related to understanding, interest, and the nature of science

Assessment Item	Yes	Somewhat	No
Did the lab(s) help you to understand…	22	2	2
Did the lab(s) increase your interest?	20	4	2
Does Science Require Experiments?	17	0	0

(h)

Fig. 19 Prepared by J. Zawicki from data collected from spring of 2011 surveys of OPT 223 and MCC students (Axis *Y* represent the number of students). (a) Most valuable aspects of quantum lab classes. (b) Least valuable aspects of quantum lab classes. (c) Most challenging aspects of quantum lab classes. (d) Suggested changes to improve the quantum lab classes. (e) Did your quantum labs help understand quantum concepts? (f) Did your quantum labs increase your interest to science? (g) Indication of several aspects of the scientific process that involve creativity (1. experimental design, 2. data collection, and 3. data analysis). (h) Understanding, interest, and the nature of science.

that there were too many students in their groups or larger rooms. (Later, we reduced a number of students in the group performing a lab experiment from 4 to 5 to 2 to 3 students by increasing a number of lab sessions). Recording their data readings did not enamor students—they would, in general like to have this task done automatically. (We had experience with an automatic data collection system using rotating mounts control from a computer, which significantly reduced the data collection time. However, we found that, a direct "hands-on" experience involving manually changing the rotation angle of polarizer/quartz plate mounts in low light conditions without destroying a system alignment will teach them how to work with fragile quantum optics equipment, while simultaneously observing all laser beam reflections from optics). Four students commented that they should be allowed to align the equipment themselves. (We had such a practice with an entanglement setup, wherein the students aligned a BBO crystals' mount; however, it took a significant amount of time to realign the system with full overlapping two SPDC cones with orthogonal polarizations.)

Student responses to the most challenging aspects of the activities are summarized in Fig. 19(c). Seven students commented on equipment usage (they wished to align it themselves and had difficulty taking readings in darkness), two students commented on the difficulty of observing interference fringes at a single-photon level, and five students commented on difficulty of generating a lab report. Five students commented on the difficulty of understanding entanglement or other quantum phenomena. Comments such as "conducting experiments in the dark," "understanding entanglement and Bell's Inequalities," and "understanding bra–ket notation used in the quantum entanglement lab lecture" are fairly representative of the general comments students provided.

The data from student comments regarding the changes that could be made to improve the activities are presented in Fig. 19(d). Students were generally positive—often suggesting that the labs are fine as they are. The comments suggested either the use of additional visualizations or simulations. While some students wished to have less direct instructions, some students asked for additional instruction about particular topics. The number of comments in this section was quite modest. We suspect that the large number of "no response" to the surveys is further indicative of student satisfaction.

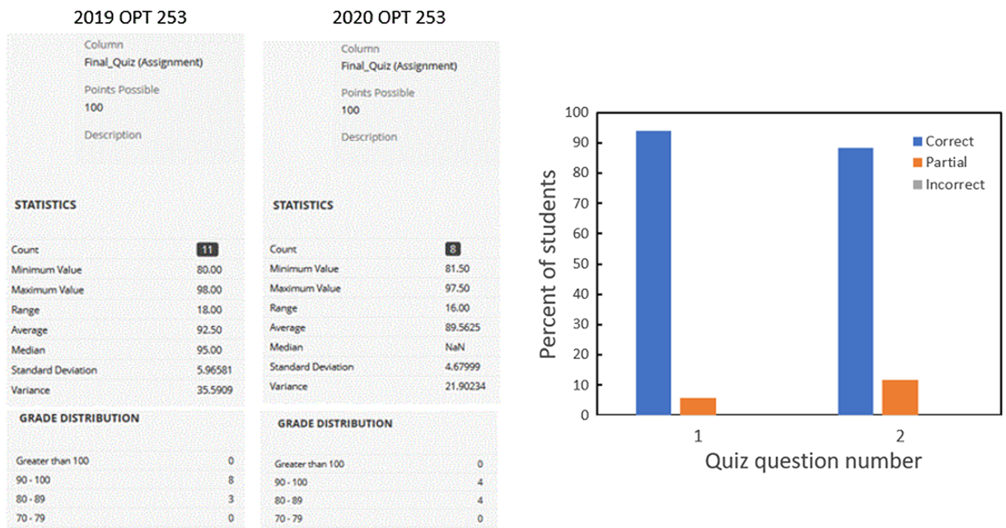
The lab activities did help students to understand—24/26 students indicated that the activities aided their understanding or reinforced what they had already learned. Only two students (8%) indicated that the activities did not help their learning. The activities also helped to spark student interest. Twenty-four students (92%) indicated that they were either more interested in this topic or that their previous interest in this topic was increased based on their lab experiences. A summary of the student responses is presented in Figs. 19(e) and 19(f).

Students generally recognized that science involves creativity and imagination. Many students indicated several aspects of the scientific process that involve creativity, including experimental design, data collection, and data analysis. The creativity data are presented in Fig. 19(g), and the overall impact of the lab activities is summarized in Fig. 19(h).

5.2 *Some of the Classes from the Academic Years 2019–2022*

In the QNOL laboratory classes, the most important exam of the whole semester is a final "Big" quiz with 50 questions regarding all four labs, consisting of 1.5 h written and 15 min oral assessments. Figure 20(a) shows the results of grading of this exam for Fall 2019 and Fall 2020 for OPT 253. The minimal grade including both years was 80%. With our previous years' experience on the most difficult questions for students on the topics of (1) antibunching and (2) entanglement, we evaluated answers to these questions from these students. The results of the survey is shown in Fig. 20(b). Practically, all 19 students answered these questions. "Partial" means that despite correct answers on antibunching, ~5% of students still did not understand that it is impossible to obtain antibunching from the laser light attenuated to a single photon level. In entanglement definition, ~10% of student did not mention its nonlocality.

In another class, OPT 204 with two quantum 3-h mini-labs (juniors-seniors), the students were examined through a "Big" quiz with 25 questions from the labs and five questions from lectures-workshops with additional materials connected to the labs. This exam also contained both 1.5-h written and 15-min oral parts with the help of TAs. Figure 21(a) shows eight questions



(a) (b)

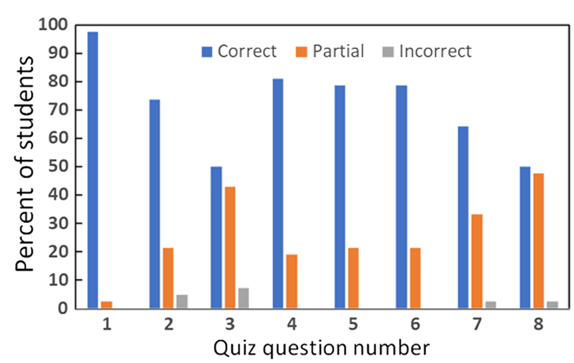
Fig. 20 (a) (from Blackboard, a virtual hub for student services that provides access to online course materials and grades): statistics of the OPT 253 class grades for a final "Big" quiz (maximum 100 points) for years 2019 and 2020. (b) Histogram of the percentage of students of OPT 253 classes (2019 + 2020) answering correctly or partially to two questions: (1) antibunching and (2) entanglement.

from this quiz. The results of grading for spring 2022 semester with 42 students are shown in Fig. 21(b). The most difficult questions were #3, which were based on the dependence of photon statistics on a coherence time of a pseudothermal source and two questions discussed on a lecture-workshop on nonclassical light sources: #7 (antibunching) and #8 (entanglement). Students of OPT 204 did not attend lab sessions on antibunching and entanglement. "Partial" refers to 32% of OPT 204 students who still think that it is possible to obtain antibunching from an attenuated laser light, and 48% of OPT 204 students did not mention nonlocality in the definition of entanglement, in contrast to OPT 253 students who had attended lab sessions on these nonclassical light sources [Fig. 20(b)].

In OPT 204 (spring 2022), we carried out surveys on students' attitude toward their career in quantum information. In addition, we performed a similar survey in this class regarding a career in nanoscience and nanotechnology (see this issue, our paper,[41] Sec. 5.4). Figure 22(a) shows the 60% of the students of this class thinking about their career in quantum optics and quantum

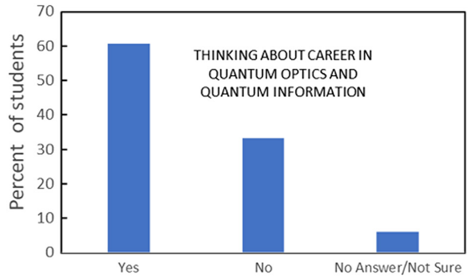
1. **How did you prepare a pseudo-thermal source from a laser light?**
2. **What is the difference in photon statistics between a laser light and a pseudo-thermal source?**
3. **How does photon statistics depend on a coherence time of a pseudo-thermal source?**
4. **How did your experiment demonstrate the wave-particle duality of photons?**
5. **Explain what is a "which-way (which-path) information". Explain it on the example of your experiments.**
6. **If light is nothing but a stream of particles (called photons), why doesn't a stream of bullets give rise to an interference pattern like that of photons?**
7. **What is photon antibunching? Can we obtain antibunching from attenuated laser pulses? Explain difference in photon statistics from laser light, thermal light at time intervals shorter than a coherence time, and antibunched light.**
8. **Finish the sentence: "Two particles are called entangled if...... How can we create photons entangled in polarization?**

(a)



(b)

Fig. 21 (a) Eight questions on quantum optics from 2022 final ("Big") quiz of the OPT 204 class. (b) Histogram of percentage of students answering these questions correctly, partially, and incorrectly.



(a)

(1) Considering your experience, are you confident that you will be able to work in a company with quantum information applications or select your career in an academy or government laboratory in this field? Are you confident that you will succeed in working in quantum information applications?

(2) If you choose a career in quantum information, what will be your work environment, what will you do on a daily basis, and what will be your work expectations? Where it will be a laboratory work or modeling?

(b)

Fig. 22 (a) Histogram of percentage of students of the OPT 204 class (2022) on their attitude toward a career in quantum optics and quantum information. (b) Two questions of the survey about self-efficacy and students' expectations regarding the future work environment in quantum information field (see results of this survey in the text).

information (34 participants). Figure 22(b) presents two questions from another survey with 23 participants about self-efficacy, future workplace, and expectations. Self-efficacy is a set of beliefs about an individual's own capacity that impact an individual's choices and the effort that they put forth to complete a task and accomplish goals.[84–86] From this survey, 60.9% of students were found to be confident that they will succeed. Some of them suggested further learning in this field; 8.7% are not confident, and 30.4% do not know how to answer. On the other hand, the answers from the same questions on self-efficacy regarding future work in nanoscience and nanotechnology revealed that only 52.2% of students of the same class are confident that they will succeed (see our paper,[41] Sec. 5.4), which is noteworthy. A possible explanation for this is that, in this class, the students only had two 15-min lab experiments related to nano-objects within four labs in contrast to two 3-h labs devoted to quantum optics experiments. The answers to the second question regarding the work environment revealed that 52.2% of students prefer a lab environment in quantum information, 17.4% prefer modeling, 13% prefer both laboratory and modeling, and 17.4% of them are not sure what their work environment will be. One student expects high salary working in quantum information.

After completion of another class, Fall 2021 QNOL, one sophomore was awarded a 2022 summer internship in a quantum-computing company after his experience in the graduate level class OPT 453.

6 Conclusion: Lessons Learned and Future Plans

We are in the midst of a second quantum revolution, which will be responsible for most of the key physical technological advances for the 21st century.[87] Many countries around the world have national programs on quantum science and technology.[88–96] The arrival of the new fields of quantum optics, quantum computation, and quantum communications and the rapid progress in photon-counting instrumentation present new opportunities for teaching the most difficult concepts of quantum mechanics using a set of simple, easily understandable, and exciting experiments with single and entangled photons. The modern reality is that high-school students already know about entanglement and some of them violate Bell's inequality at their home setup; for instance, see Ref. 26.

The goal of this paper is sharing 15 years of experience of the Institute of Optics, UR, in preparing every optics student to a second quantum revolution. We introduced sturdy quantum optics lab experiments to classes from freshman to senior and graduate student levels, so every optics student learns quantum optics concepts in practice by doing lab experiments with photon counting instrumentation. We increased the diversity of involved students by collaborating with a local community college and bringing its students to the UR to carry out 3-h quantum mini-labs at the UR.

This paper provides a description of these studies, including universally accessible quantum optics experiments (3-h mini-labs) that can be introduced into either a separate advanced lab class on quantum optics or lab or lecture classes with a large number of students. These quantum mini-labs are based on the upper-level, advanced laboratory, whole semester QNOL class with 11 lab sessions, and its structure is discussed in detail. Our methods and lab experiments can be adopted by other universities and colleges.

Assessments methods and results of analyzing the outcomes for classes with different levels of students' knowledge as well as some quizzes' questions are also discussed. Moreover, the students' self-efficacy evaluation and their expectations for future possible careers in quantum information are provided.

Currently, the QNOL facility lacks a Hong-Ou-Mandel interferometer[97] lab (two-photon quantum interference on a beam-splitter), which will be built in the future in combination with entanglement setup. Using a poled fiber phase matched for type II downconversion[98] can significantly simplify alignment of entanglement setup. Currently, a Hong-Ou-Mandel effect is discussed only in lectures both in advanced QNOL classes and required for optics major OPT 204 class. It was first obtained at the UR and one of its practical applications is quantum computing. On an example familiar to the OPT 204 students, who measured reflectivity of liquid crystal photonic bandgap materials, experiments on single-photon tunneling times with femtosecond resolution through structures with liquid crystals, which were performed using this interferometer,[99–101] are also discussed.

The main lesson learned from our experience is that the laboratory approach to studying the basic concepts of quantum science makes it possible to successfully teach students with high-school knowledge of science. We also have firsthand experience with the UR Laboratory for Laser Energetics, high-school intern, and NSF-funded "Research Experience for Teachers" programs. The participants we mentored in quantum projects became our coauthors in scientific publications.[102,103] One high school student reached semifinalist status in the Intel Science Talent Search competition (2004) for her successful project in quantum nanophotonics.[102] The second, important lesson derives from our study of students' surveys stressing that visualizations and simulations facilitate students' learning. Following this feedback, we included some animated pictures from internet[104] to the lectures. As a further step in this direction, quantum games will be employed; see, for instance, Ref. 105 that provides an overview and guidelines for incorporating quantum games and interactive tools in pedagogic materials to make quantum technologies more accessible for a wider population. Another way to attract young people's interest is called quantum internet[106] with its practical realization (QKD and quantum repeaters).

The average undergraduate student finds quantum physics's mathematical tools most challenging. Although in traditional quantum mechanics introduction courses, for instance, in Ref. 107, the EPR paradox and Bell's theorem were included as afterword chapters, a new type of textbooks[108] starts with students' topics of interest (quantum cryptography, entanglement, EPR paradox, Bell's inequality, decoherence, quantum computing and quantum teleportation), but at the same time in later lectures all traditional topics of quantum physics are also covered in-depth (Schrödinger equation, harmonic oscillator, hydrogen atom, etc.). An interesting approach to teaching mathematical tools of quantum physics is implemented in the book[109] written by a well-known quantum information science researcher with participation by two high school students as his coauthors and illustrated by a graduate student. Our future task is to find the optimal combination of a laboratory approach in teaching quantum physics with teaching mathematical tools essential for its understanding.

In conclusion, the QNOL facility at the Institute of Optics became the basis for training future optics engineers in single-photon counting instrumentation, toward "achieving a quantum smart workforce."[44–47,78] Several professors in quantum optics, former students of the advanced QNOL classes, work in the United States, Europe, and Asia's leading universities.

The results of this paper were discussed at two International Conferences on Education and Training in Optics and Photonics (ETOP)[36,37] of 2017 and 2021 and at Rochester Conference on Coherence and Quantum Optics (CQO-11)[38] of 2019.

Acknowledgments

The author acknowledges the support by the US Army Research Office (Award No. DAAD19-02-1-0285); the National Science Foundation (NSF; Award Nos. ECS-0420888, DUE-0633621, DUE-0920500, EEC-1343673); the University of Rochester Kauffman Foundation Initiative, Wadsworth C. Sykes Faculty Engineering Award, the Hajim School of Engineering and Applied Sciences (University of Rochester); donation from Spectra-Physics; and constant support by the Institute of Optics. The author also thanks C.R. Stroud for his support and collaboration, P. D'Alessandris for collaboration, J. Zawicki for evaluation of students' learning, W. Knox and T. Brown for collaboration with freshman projects, P. Adamson and E. Herger for their help and support with teaching lab equipment, A.K. Jha and J. Choi for their contributions to entanglement setups, L.J. Bissell for his contribution to a single-photon source generation and characterization unit, L. Novotny and A. Lieb for their help on initial stage of the project and for providing imaging software, J. Rutledge for writing photon statistics program, R.W. Boyd and his group members for the help, and all TAs of QNOL and OPT 204 classes during these years. Special thanks to B. Zwickl for discussion and providing some references. The author also grateful to A. Ariyawansa and R. Lopez-Rios for some of prepared figures. The author acknowledges reviewers' comments and Editage's editorial support.

References

1. C. Singh, M. Belloni, and W. Christian, "Improving students' understanding of quantum mechanics," *Phys. Today* **59**(8), 43–49 (2006).
2. C. Singh, "Student understanding of quantum mechanics," *Am. J. Phys.* **69**(8), 885–895 (2001).
3. C. Singh, "Student understanding of quantum mechanics at the beginning of graduate instruction," *Am. J. Phys.* **76**(3), 277–287 (2008).
4. C. Singh, "Interactive learning tutorials on quantum mechanics," *Am. J. Phys.* **76**(4&5), 400–405, (2008).
5. C. Singh and E. Marshman, "Review of student difficulties in upper-level quantum mechanics," *Phys. Rev. ST Phys. Educ. Res.* **11**, 020117 (2015).
6. C. Baily and N. D. Finkelstein, "Teaching and understanding of quantum interpretations in modern physics courses," *Phys. Rev. ST Phys. Educ. Res.* **6**, 010101 (2010).
7. S. Goldhaber et al., "Transforming upper-division quantum mechanics: learning goals and assessment," in *AIP Conf. Proc.*, Vol. 1179, pp. 145–148 (2009).
8. E. H. Carlson, "Constructing laboratory courses," *Amer. J. Phys.* **54**, 972 (1986).
9. AAPT, "Recommendations for the undergraduate physics laboratory curriculum," Report prepared by a Subcommittee of the AAPT Committee on Laboratories (Endorsed by the AAPT Executive Board, November 10, 2014). https://www.aapt.org/resources/upload/labguidlinesdocument_ebendorsed_nov10.pdf (accessed 7 July 2022).
10. D. Dehlinger and M. W. Mitchell, "Entangled photon apparatus for the undergraduate laboratory," *Am. J. Phys.* **70**, 898–902 (2002).
11. D. Dehlinger and M. W. Mitchell, "Entangled photons, nonlocality, and Bell inequalities in the undergraduate laboratory," *Am. J. Phys.* **70**, 903–910 (2002).
12. E. J. Galvez, "Resource letter SPE-1: single-photon experiments in the undergraduate laboratory," *Am. J. Phys.* **82**, 1018–1028 (2014).
13. E. J. Galvez, "Qubit quantum mechanics with correlated photon experiments," *Am. J. Phys.* **78**, 510–519 (2010).
14. E. J. Galvez et al., "Interference with correlated photons: five quantum mechanics experiments for undergraduates," *Am. J. Phys.* **73**, 127–140 (2005).
15. J. J. Thorn et al., "Observing the quantum behavior of light in an undergraduate laboratory," *Am. J. Phys.* **72**, 1210–1219 (2004).
16. A. Gogo, W. D. Snyder, and M. Beck, "Comparing quantum and classical correlations in a quantum eraser," *Phys. Rev. A* **71**, 052103 (2005).
17. A. Bista, B. Sharma, and E. J. Galvez, "A demonstration of quantum key distribution with entangled photons for the undergraduate laboratory," *Am. J. Phys.*, **89**(1), 111–120 (2021).
18. E. J. Galvez, "Remote quantum optics labs," *Proc. SPIE* **11701**, 1170106 (2021).
19. E. Z. Galvez and M. Beck, "Quantum optics experiments with single photons for undergraduate laboratories," *Proc. SPIE* **9665**, 966513.
20. E. Z. Galvez, "Photon quantum mechanics," https://egalvez.colgate.domains/pql/ (accessed 7 July 2022).

21. M. Beck, *Quantum Mechanics. Theory and Experiment*, Oxford University Press, Oxford, New York (2012).
22. M. Beck, "Modern undergraduate quantum mechanics experiments," http://people.reed.edu/~beckm/QM/ (accessed 7 July 2022).
23. D. Branning, S. Bhandari, and M. Beck, "Low-cost coincidence-counting electronics for undergraduate quantum optics," *Am. J. Phys.* **77**, 667–670 (2009).
24. M. N. Beck and M. Beck, "Witnessing entanglement in an undergraduate laboratory," *Am. J. Phys.* **84**, 87 (2016).
25. M. H. Waseem, F. e-Ilahi, and M. S. Anwar, *Quantum Mechanics in the Single Photon Laboratory*, IOP Publishing (2020).
26. D. Prutchi and S. R. Prutchi, *Exploring Quantum Physics through Hands-on-Projects*, Wiley, New Jersey (2012).
27. M. B. Schneider and I. A. LaPuma, "A simple experiment for discussion of quantum interference and which-way measurements," *Am. J. Phys.* **70** (3), 266 (2002).
28. J. Castrillon et al., "A time-energy delayed-choice interference experiment for the undergraduate laboratory," *Eur. J. Phys.* **40**, 055401 (2019).
29. B. J. Pearson and D. P. Jackson, "A hands-on introduction to single photons and quantum mechanics for undergraduates," *Am. J. Phys.* **78**, 471–484 (2010).
30. P. Koczyk, P. Wiewior, and C. Radzewicz, "Photon counting statistics—undergraduate experiment," *Am. J. Phys.* **64**, 240–245 (1996).
31. C. Funk and M. Beck, "Sub-Poissonian photocurrent statistics: theory and undergraduate experiment," *Am. J. Phys.* **65**, 492–500 (1997).
32. H. Holbrow, E. Galvez, and M. E. Parks, "Photon quantum mechanics and beam splitters," *Am. J. Phys.* **70**, 260–265 (2002).
33. R. S. Aspden, M. J. Padgett, and G. C. Spalding, "Video recording true single-photon double-slit interference," *Am. J. Phys.* **84**, 671–677 (2016).
34. President's Council of Advisors on Science and Technology, "Engage to excel: producing one million additional college graduates with degrees in science, technology, engineering and mathematics," Report to the President, Released Feb 7 (2012).
35. S. G. Lukishova, "10. Quantum optics laboratory," in *A Jewel in the Crown II: Essays in Honor of the 90th Anniversary of the Institute of Optics*, G. Kern and C. R. Stroud Jr., Eds., pp. 65–68, Meliora Press, University of Rochester (2020).
36. S. G. Lukishova, "Quantum optics and nano-optics teaching laboratory for the undergraduate curriculum: teaching quantum mechanics and nano-physics with photon counting instrumentation," *Proc. SPIE* **10452**, 104522I.
37. S. G. Lukishova, "15 years of quantum optics educational facility at the Institute of Optics, University of Rochester," in *Educ. and Train. in Opt. & Photonics (ETOP) Conf.*, 8–10 September, Optica Publishing Group, Washington, DC, p. W2B.3 (2021).
38. S. G. Lukishova, "13 years of quantum optics, quantum information and nano-optics teaching laboratory facility at the Institute of Optics, University of Rochester," in *Proc. Rochester Conf. Coherence and Quantum Opt.*, 48 August, Rochester, New York (2019).
39. S. G. Lukishova, N. P. Bigelow, and P. D. D'Alessandris, "Development of multidisciplinary nanotechnology undergraduate education program at the University of Rochester Integrated Nanosystems Center," *Proc. SPIE* **10452**, 104521O (2017).
40. S. G. Lukishova, "Undergraduate program in nanoscience and nanoengineering: 5 years after the NSF Grant," in *Educ. and Train. in Opt. & Photonics (ETOP) Conf.*, 8–10 September, Optica Publishing Group, Washington, DC, p. F1A.6 (2021).
41. S. G. Lukishova and N. P. Bigelow, "Undergraduate program in nanoscience and nanoengineering: 5 years after the NSF grant including 2 pandemic years," *Opt. Eng.*, **61**(8), 081810 (2022).
42. S. G. Lukishova, "Quantum optics, quantum information and nano-optics laboratory," http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/ (accessed 7 July 2022).
43. National Quantum Initiative, https://www.quantum.gov/ (accessed 7 July 2022). See also QIST Workforce Development (A Report by the Subcommittee on Quantum Information

Science), https://www.quantum.gov/wp-content/uploads/2022/02/QIST-Natl-Workforce-Plan.pdf (accessed 7 July 2022).
44. M. F. J. Fox, B. M. Zwickl, and H. J. Lewandowski, "Preparing for the quantum revolution: what is the role of higher education?" *Phys. Rev. Phys. Educ. Res.* **16**, 020131 (2020).
45. C. D. Aiello et al., "Achieving a quantum smart workforce," *Quantum Sci. Technol.* **6**, 030501 (2021).
46. A. Asfaw et al. "Building a quantum engineering undergraduate program," *IEEE Trans. Educ.* **65**(2), 220–242 (2022).
47. C. Singh, A. Asfaw, and J. Levy, "Preparing students to be leaders of the quantum information revolution," *Phys. Today*, 27 Sept. 2021, https://physicstoday.scitation.org/do/10.1063/pt.6.5.20210927a/full/. See also https://arxiv.org/ftp/arxiv/papers/2111/2111.06438.pdf (accessed 13 July 2022).
48. National Q12 Education Partnership, https://q12education.org/ (accessed 7 July 2022). See also The Quantum Economic Development Consortium (QED-C), https://quantumconsortium.org/tac/ (accessed 7 July 2022).
49. S. G. Lukishova and L. J. Bissell, "Nanophotonic advances for room-temperature single-photon sources," in *Quantum Photonics: Pioneering Advances and Emerging Applications*, R. W. Boyd, S. G. Lukishova, and V. N. Zadkov, Eds., Springer Series in Optical Sciences, Vol. 217, pp. 103–178, Springer Nature Switzerland AG (2019).
50. A. Einstein, B. Podolsky, and N. Rosen, "Can quantum-mechanical description of physical reality be considered complete?" *Phys. Rev.* **47** (10), 777–780 (1935).
51. E. Schrödinger, "Discussion of probability relations between separated systems," *Proc. Cambridge Philos. Soc.* **31**, 555–563 (1935).
52. N. Bohr, "Can quantum-mechanical description of physical reality be considered complete?" *Phys. Rev.* **48**, 696–702 (1935).
53. J. Bell, "On the Einstein Podolsky Rosen paradox," *Physics* **1** (3), 195–200 (1964).
54. J. S. Bell, *Speakable and Unspeakable in Quantum Mechanics: Collected Papers on Quantum Philosophy, Introduction of Aspect A*, Cambridge University Press, Cambridge, New York (2004).
55. J. H. Eberly, "Bell inequalities and quantum mechanics," *Am. J. Phys.* **70**(3), 276–279 (2002).
56. J. F. Clauser et al., "Proposed experiment to test local hidden-variable theories," *Phys. Rev. Lett.* **23**, 880–884 (1969).
57. P. G. Kwiat et al., "Ultrabright source of polarization-entangled photons," *Phys. Rev. A.* **60**, R773–R776 (1999).
58. L. Mandel and E. Wolf, *Optical Coherence and Quantum Optics*, Cambridge University Press, New York (1995).
59. A. Rae, *Quantum Physics: Illusion or Reality*, Cambridge University Press, Cambridge, London, New York (1986).
60. M. Fox, *Quantum Optics. An Introduction*, Oxford University Press, Oxford, New York (2007).
61. G. Greenstein and A. G. Zajonc, *The Quantum Challenge. Modern Research on the Foundations of Quantum Mechanics*, Jones and Bartlett, Boston, Toronto (2006).
62. M. S. Zubaru, *Quantum Mechanics for Beginners (With Application to Quantum Communication and Quantum Computing)*, Oxford University Press, New York (2020).
63. E. G. Steward and S. M. McMurry, *Quantum Mechanics. Its Early Development and the Road to Entanglement and Beyond, New Enlarged Edition*, Imperial College Press, London (2012).
64. D. N. Klyshko, *Photons and Nonlinear Optics*, Gordon and Breach, New York (1988).
65. S. G. Lukishova, "The first paper on experimental observation of interference fringes with feeble light (Sir Geoffrey Ingram Taylor)," in *Quantum Photonics: Pioneering Advances and Emerging Applications*, R. W. Boyd, S. G. Lukishova, and V. N. Zadkov, Eds., Springer Series in Optical Sciences, Vol. 217, pp. 419–424, Springer Nature Switzerland AG (2019).
66. G. Gbur and T. D. Visser, "Young's interference experiment: past, present, and future," *Progr. Opt.* **67**, 275–343 (2022).

67. S. G. Lukishova, "The first nonlinear optical experiment of 1926, measuring sensitivity threshold of the human eye to feeble light (1933) and statistical structure of feeble-light interference by the human eye (Sergei Ivanovich Vavilov)," in *Quantum Photonics: Pioneering Advances and Emerging Applications*, R. W. Boyd, S. G. Lukishova, and V. N. Zadkov, Eds., Springer Series in Optical Sciences, Vol. 217, pp. 481–542, Springer Switzerland AG (2019).
68. S. G. Lukishova, "Measuring sensitivity threshold of the human eye to feeble light (Selig Hecht)," in *Quantum Photonics: Pioneering Advances and Emerging Applications*, R. W. Boyd, S. G. Lukishova, and V. N. Zadkov, Eds., Springer Series in Optical Sciences, Vol. 217, pp. 555–586, Springer Nature Switzerland AG (2019).
69. H. J. Kimble, M. Dagenais, and L. Mandel, "Photon antibunching in resonance fluorescence," *Phys. Rev. Lett.* **39**, 691–695 (1977).
70. D. F. Walls, "Evidence for the quantum nature of light," *Nature* **280**, 451–454 (1979).
71. A. Migdall et al., Eds., *Single-Photon Generation and Detection*, Elsevier (2013).
72. R. Hanbury Brown and R. Q. Twiss, "Correlation between photons in two coherent beams of light," *Nature* **177**, 27–29 (1956).
73. S. G. Lukishova and W. J. Tango, "First observation of photon correlations (bunching) with beamsplitter and photomultipliers (Robert Hanbury Brown and Richard Quintin Twiss)," in *Quantum Photonics: Pioneering Advances and Emerging Applications*, R. W. Boyd, S. G. Lukishova, and V. N. Zadkov, Eds., *Springer Series in Optical Sciences*, Vol. 217, pp. 605–620, Springer Nature Switzerland AG (2019).
74. S. G. Lukishova et al., "Plasmonic bowtie nanoantennas with nanocrystal quantum dots for single-photon source applications," Frontiers in Optics 2016, OSA Technical Digest, (Optical Society of America, Rochester NY, September 17–21, 2016), paper LF2D.6,
75. S. G. Lukishova et al., "Ultrabright photoluminescence spikes and stepwise photoluminescence increase from colloidal silver nanoparticles for patch nanoantennas," *J. Phys.: Conf. Ser.* **2249**, 012002 (2022).
76. Advanced Laboratory Physics Association, https://advlab.org/ (accessed 7 July 2022).
77. S. G. Lukishova, "Liquid crystals under two extremes: (1) high-power laser irradiation, and (2) single-photon level," *Mol. Cryst. Liq. Cryst.* **559**(1), 127–157 (2012).
78. A. S. Szurak et al., "Development of an undergraduate quantum engineering degree," *IEEE Trans. Quantum Eng.* **3**, 6500110 (2022).
79. A. Hofstein and V. N. Lunetta, "The laboratory in science education: foundations for the twenty-first century," *Sci. Educ.* **88**(1), 28–54 (2004).
80. B. M. Zwickl, N. Finkelstein, and H. J. Lewandowski, "The process of transforming an advanced lab course: goals, curriculum, and assessments," *Am. J. Phys.* **81**(1), 63–70 (2013).
81. J. T. Stanley and H. J. Lewandowski, "Recommendations for the use of notebooks in upper-division physics lab courses," *Am. J. Phys.* **86**(1), 45–53 (2018).
82. A. Karelina and E. Etkina, "Acting like a physicist: student approach study to experimental design," *Phys. Rev. ST Phys. Educ. Res.* **3**, 020106 (2007).
83. N. G. Holmes and C. E. Wieman, "Introductory physics labs: we can do better," *Phys. Today* **71**(1), 38–45 (2018).
84. A. Bandura, "Self-efficacy: toward a unifying theory of behavioral change," *Psychol. Rev.* **84**, 191 (1977).
85. A. Bandura, "Social cognitive theory: an agentic perspective," *Annu. Rev. Psychol.* **52**, 1 (2001).
86. D. Zohrabi Alaee, M. K. Campbell, and B. M. Zwickl, "Impact of virtual research experience for undergraduates experiences on students' psychosocial gains during the COVID-19 pandemic," *Phys. Rev. Educ. Res.* **18**, 010101 (2022).
87. J. P. Dowling and G. J. Milburn, "Quantum technology: the second quantum revolution," *Philos. Trans. R. Soc. London Ser. Math. Phys. Eng. Sci.* **361**(1809), 1655–1674 (2003).
88. R. Thew, T. Jennewein, and M. Sasaki, "Focus on quantum science and technology initiatives around the world," *Quantum Sci. Technol.* **5**(1), 010201 (2020).
89. P. Knight and I. Walmsley, "UK national quantum technology programme," *Quantum Sci. Technol.* **4**(4), 040502 (2019).

90. M. G. Raymer and C. Monroe, "The US national quantum initiative," *Quantum Sci. Technol.* **4**(2), 020504 (2019).
91. M. Riedel et al., "Europe's quantum flagship initiative," *Quantum Sci. Technol.* **4**(2), 020501 (2019).
92. A. K. Fedorov et al., "Quantum technologies in Russia," *Quantum Sci. Technol.* **4**(4) 040501 (2019).
93. Q. Zhang et al., "Quantum information research in China," *Quantum Sci. Technol.* **4**(4), 040503 (2019).
94. B. Sussman et al., "Quantum Canada," *Quantum Sci. Technol.* **4**(2) 020503 (2019).
95. Y. Yamamoto, M. Sasaki, and H. Takesue, "Quantum information science and technology in Japan," *Quantum Sci. Technol.* **4**(2), 020502 (2019).
96. M. Roberson and A. G. White, "Charting the Australian quantum landscape," *Quantum Sci. Technol.* **4**(2), 020505 (2019).
97. C. K. Hong, Z. Y. Ou, and L. Mandel, "Measurement of subpicosecond time intervals between two photons by interference," *Phys. Rev. Lett.* **59**(18), 2044–2046 (1987).
98. C. Chen et al., "Telecom-band hyperentangled photon pairs from a fiber-based source," *Phys. Rev. A* **105**(4), 043702 (2022).
99. G. M. Gehring et al., "Time-domain measurements of reflection delay in frustrated total internal reflection," *Phys. Rev. Lett.* **111**, 030404 (2013).
100. A. C. Liapis et al., "Time-domain measurements of single photon tunneling phenomena," in *10th Rochester Conf. Coherence and Quantum Opt. (CQO-X)*, 17–20 June, Technical Digest on CD, paper G-M6.51, Rochester, NY (2013).
101. A. C. Liapis et al., "Temporal reshaping of single photon wave packets using cholesteric liquid crystals," in *Front. in Opt./Laser Sci. Conf.*, 14–18 October, Technical Digest on CD, paper LTu4J.7, Rochester, New York (2012).
102. S. G. Lukishova et al., "Dye-doped cholesteric-liquid-crystal room-temperature single photon source," *J. Mod. Opt.* **51**(9–10), 1535–1547 (2004).
103. S. G. Lukishova et al., "Single-photon source for quantum information based on single dye molecule fluorescence in liquid crystal host," *Mol. Cryst. Liq. Cryst.* **454**, 403–416 (2006).
104. B. Cameron (uploader), "Dr Quantum – double slit experiment," https://archive.org/details/youtube-DfPeprQ7oGc (accessed 7 July 2022). This clip is used for educational purposes. It is from *What the Bleep Do We Know!?: Down the Rabbit Hole*, DVD (2006).
105. Z. C. Seskir et al., "Quantum games and interactive tools for quantum technologies outreach and education," *Opt. Eng.*, **61**(8), 081809 (2022).
106. J. P. Dowling, *Schrödinger's Web. Race to Build the Quantum Internet*, CRC Press, Boca Raton (2021).
107. D. J. Griffiths, *Introduction to Quantum Mechanics*, 2nd ed., Pearson Prentice Hall, Upper Saddle River, New Jersey (2005).
108. A. I. Lvovsky, *Quantum Physics. An Introduction Based on Photons*, Undergraduate Lecture Notes in Physics, Springer-Verlag, Berlin (2018).
109. V. Scarani, C. Lynn, and L. S. Yang, *Six Quantum Pieces. A First Course in Quantum Physics*, Undergraduate Lecture Notes in Physics, World Scientific, Singapore (2010).

Svetlana G. Lukishova is currently a group leader at the Institute of Optics, University of Rochester, where she has worked for more than 20 years. Her research interests include quantum nanophotonics, liquid crystals, and nonlinear optics with more than 250 publications. She served as a topical editor of *Optics Letters* for six years. She created and directs the University of Rochester Undergraduate Certificate Program in Nanoscience and Nanoengineering based on the Quantum Optics and Nano-Optics Laboratory Facility.