QUANTUM OPTICS LABORATORY FOR THE UNDERGRADUATE CURRICULUM: TEACHING QUANTUM MECHANICS WITH PHOTON COUNTING EQUIPMENT

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1. INTRODUCTION

Quantum mechanics is one of the most challenging topics of modern physics in science and engineering education, but it is now being applied to important technological problems. Enormously powerful computers and total communication security are the future goals of quantum information technology which is emerging in the market. It is important to familiarize the future workforce with these new ideas as well as to provide them with hands-on experience in photon-counting instrumentation widely used in many technological areas (e.g., nanotechnology and biomedicine). At the Institute of Optics, University of Rochester, we have adapted to the main challenge (the lack of space in the curriculum) by developing a series of modular 3-hour experiments and 20-min-demonstrations based on technical elective, 4-credit-hour laboratory course [1], that were incorporated into a number of courses ranging from freshman to senior level, in both physics and engineering. Rochester Monroe Community College students also benefited from this facility (supported by three NSF grants) by carrying out two 3-hour labs at the University of Rochester. Since 2006, total 134 students (32 diverse groups) passed through the labs with lab report submission and more than 150 students (~13 groups) through lab demonstrations.

Four labs were prepared on 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) confocal microscope imaging of single-emitter fluorescence, (4) Hanbury Brown and Twiss setup. Fluorescence antibunching. Manuals, student reports, presentations and lecture materials are placed on a website [1]. In addition to 4-credit-hour technical elective course, these labs are included to the following University of Rochester and Monroe Community college courses: "Quantum Mechanics of Optical Materials and Devices" OPT 223 (two 3-hour labs), freshmen course "Optics in the Information Age" OPT 101 (12-hour research projects), "Modern Physics" (two 3-hour labs). We started the NSF CCLI Phase II project "Diverse Partnership for Teaching Quantum Mechanics and Modern Physics with Photon Counting Instrumentation". This project scope is the development of a set of 1.5 - 3 hour teaching experiments for quantum mechanics and modern physics courses at a diverse range of colleges and Universities. I participate in the immersion program of the Advanced Laboratory Physics Association [2] to disseminate my experience to another universities.

2. DESCRIPTION OF PREPARED TEACHING EXPERIMENTS

Lab. 1. Entanglement and Bell's inequalities

The schematic of teaching experiment to produce polarization-entangled photons and Bell's inequalities' violation measurements is shown in the Figure 1, top left. We implemented and developed the setups of Refs. [3-5].

In this experiment, we use spontaneous parametric down conversion process in two type-I BBO crystals. We have two modifications of the experiments: with a diode laser and with an argon ion laser. In the first modification, light from a 10 mW, 405 nm, cw diode laser passes through a blue filter and then a quartz plate. A mirror redirects the beam through a pair of BBO crystals that are mounted back-to-back with one rotated 90^o from the other about the beam propagation direction. Down-converted photons from the crystals are detected by a pair of single-photon counting avalanche photodiode modules (APDs) mounted on the rails. This enables these two APDs to be on two diametrically opposite points of the down-converted cone. In this arrangement each crystal can support downconversion of one pump polarization. Using the same experiment, but a more powerful 100 mW, 363. 8 nm, cw argon ion laser and a thicker type I BBO crystal set permitted us to built a setup (photos of Figure 1, top right) with very reproducible results for quick demonstration of photon entanglement during only 2 hours of "mini-lab" for several groups of students of different levels. All groups of students obtained very high visibility fringes of coincidence count (~0.9) showing possibility of photon entanglement.

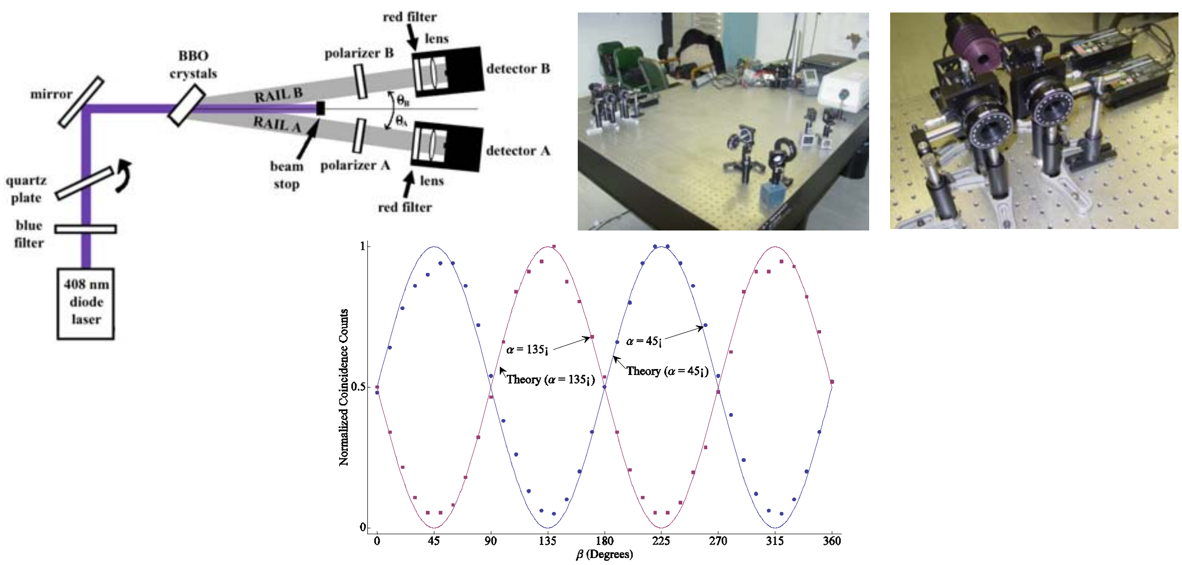

Figure 1. Top left: schematics of entanglement and Bell's inequalities experiment with a blue diode laser; top right: photographs of entanglement lab setup and entangled photon registration module of an argon ion laser setup; bottom: experimental polarization correlations.

A 45^o polarized pump photon can downconvert in either crystal, producing a polarization entangled pair of photons. Quartz plate rotation compensates phase Δ introduced by the crystals.

$$|H\rangle + |V\rangle \rightarrow |V_s V_i\rangle + \exp(i\Delta)|H_s H_i\rangle$$

Coincidences are detected by a fast logic circuit (counter) card inside a PC. Figure 1, bottom shows $\sim\cos^2(\alpha-\beta)$ coincidence count dependence on a relative angle $\alpha-\beta$ between two linear polarizers A and B located in front of each APD. In this experiment an angle β of the linear polarizer B varies at two different fixed angles α of the polarizer A. Calculation of Bell's inequality in the Clauser-Horn-Shimony-Holt form shows its violation (S~2.65 > 2).

Lab 2. Single photon interference (Young's double slit experiment and Mach-Zehnder interferometer)

Young's double slit experiment with single photons shows wave-particle duality. Measurements were made using He-Ne laser beam, attenuated to a single photon level, and EM, cooled CCD camera iXon of Andor Technologies. Figure 2, left shows the results of measurements. Mach-Zehnder interferometer (Figure 2, right) is used for the demonstration of a single-photon interference after removing "which-way" information (identification of the path). See also similar undergraduate experiments in Ref. 6.

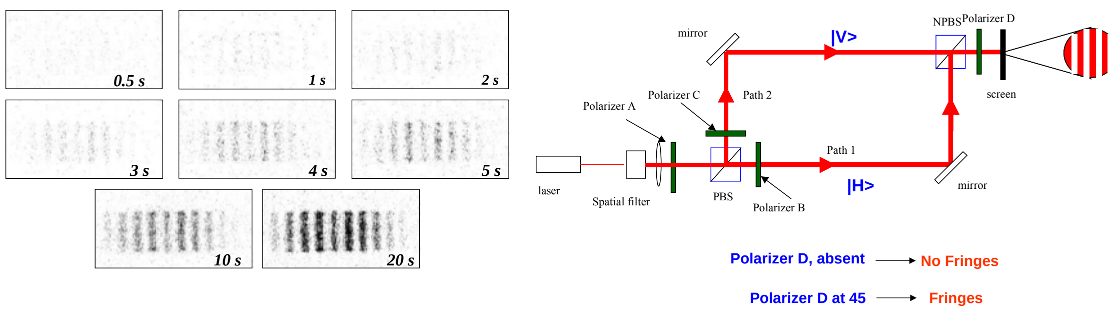

Figure 2, Left: single-photon interference using Young's double-slit at different exposure time. Right: Mach-Zehnder interferometer schematics for "which-way experiment.

Lab 3. Confocal microscope imaging of single-emitter fluorescence

Labs 3 and 4 are devoted to single (antibunched) photon source, a key hardware element in quantum cryptography. 8 ps pulse duration, 76 MHz pulse repetition rate laser excitation at 532-nm is used for confocal microscope single-emitter fluorescence imaging (Figure 3). Single molecules of DiI dye, colloidal semiconductor quantum dots and color centers in nanodiamonds are used as single emitters.

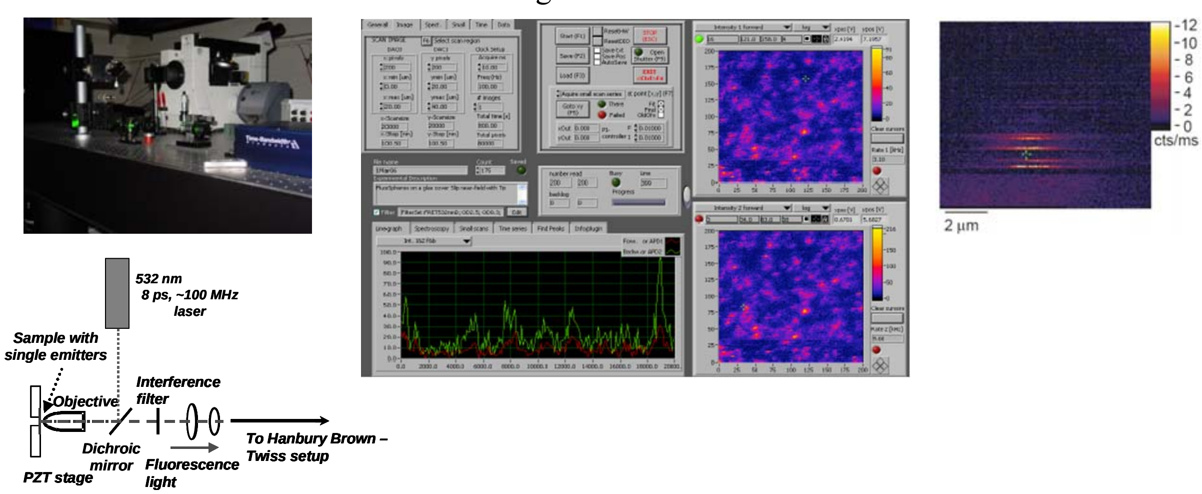

Figure 3. Left: Photograph and schematic of a home-built confocal microscope; center: user interface for single-emitter fluorescence imaging. Images of a raster scan of the sample show DiI-dye single-molecule fluorescence; right - single PbSe quantum dot fluorescence image in 1-D photonic bandgap liquid crystal host (800 nm fluorescence maximum).

Students enrolled in the laboratory course also participated in research. They carried out imaging of single PbSe quantum dot fluorescence in photonic bandgap cholesteric liquid crystal host (Figure 3, right shows "blinking" of quantum dot). PbSe quantum dots are very important for single-photon source operating at optical communication wavelengths.

Lab. 4. Hanbury Brown and Twiss setup. Fluorescence antibunching

Students record changes of fluorescence intensity of single quantum dot in time (Figure 4, left). Figure 4, right shows Hanbury Brown and Twiss setup for fluorescence antibunching measurements. It consists of a nonpolarizing 50:50 beamsplitter forming two arms. The time interval τ between two consecutively detected photons in separate arms is measured by a TimeHarp 200 PC time-correlated single-photon counting card using a conventional start-stop protocol. This coincidence-event distribution is proportional to the autocorrelation function $g^{(2)}(\tau)$. For single photons, $g^{(2)}(0)=0$ indicating the absence of pairs, or antibunching. Figure 5 shows antibunching curves with the dips at $\tau = 0$ indicating antibunching. The antibunching dip at time interval $\tau = 0$ on the correlation events histogram is a proof of the single-photon nature of the source.

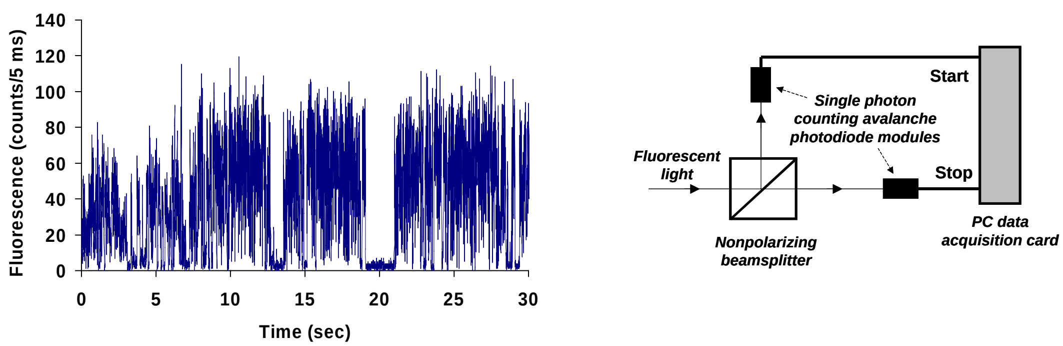

Figure 4. Left: changes of fluorescence intensity of single CdSeTe quantum dot in time (blinking); right: schematics of a Hanbury Brown and Twiss setup for fluorescence antibunching measurements,

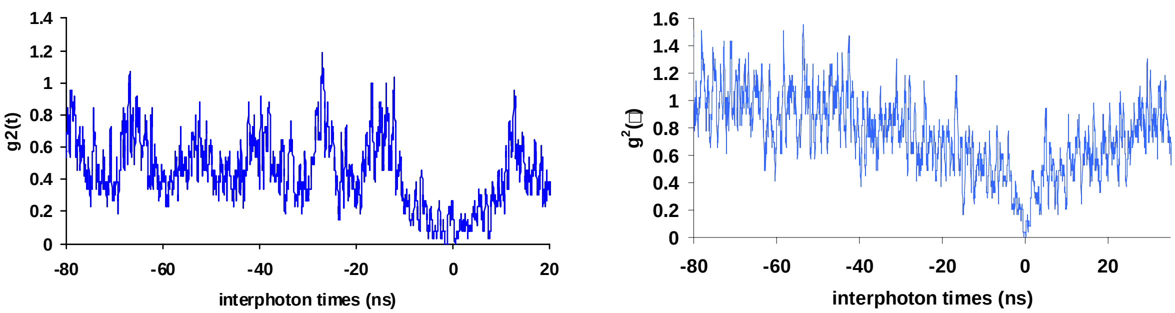

Figure 5. Left: fluorescence antibunching of single PbSe quantum dot on bare glass slip under pulsed laser excitation; right: fluorescence antibunching of single CdSeTe quantum dot in 1-D photonic bandgap cholesteric liquid crystal host (fluorescence lifetime of quantum dots is higher than the time interval between laser pulses).

3. ASSESSMENT METHODS

Multiple forms of assessment methods varied depending of a particular student group and the time students spent in the lab (3-15 hours): writing individual/group lab reports and essays, preparing individual/group presentations, exams with detailed answering 7-36 questions, etc. For the full 4-credit-hour course, performance assessment methods were also used, e.g., debating a topic, demonstrating a skill, presenting the laboratory notebooks. During the discussion with each student, students were asked to defend their scientific arguments because some questions permitted different types of answers. To recognize and analyze alternative explanations and models students were asked to write the essays on alternative technologies of single/entangled photon sources. For communication skills development sometimes students were divided into groups of two or three students. Maximum student number in the group was six.

Ungraded written and oral practice Mid term and Final exams for the full four-credit-hour course significantly contributed to the project's success. Technical problems have been worked out after practice exams during special lectures. Started from 2010 Fall, ungraded pre-tests were also used before each lab after reading lab manuals, and at the end of each lab.

Some assessment methods measured meaningful learning outcomes, e.g., one of criteria of project success in 2009-2012 is that 80% of students of 4-credit-hour course should have correct answers for 70% of the questions. We are still working on the criteria of success for freshmen, community college and undergraduate students of courses with three-hour ("mini") labs. For these groups of students we are investigating student capability to learn difficult concepts in a restricted time frame. Before the lab sessions, the lectures and discussions devoted to lab contents are included in all courses which incorporate two-3-hour lab sessions.

Learning outcomes describe what students are able to demonstrate in terms of knowledge and skills upon completion of the full lab course or the lab. We have three learning measurable outcomes: (a) students are able to demonstrate knowledge of the concepts of entanglement, quantum superposition and interference, wave-particle duality, single photons; (b) students demonstrate mastery in photon-counting instrumentation; (c) students are involved in research, combining research and education.

Teaching assistants help in summative evaluation. For instance, using a questionnaire with 36 questions on photon quantum mechanics in 2008, showed that one half students of 4-credit hour course answered correctly more than 75% of questions, 70% of students answered correctly more than 70% of questions and all students answered correctly more than 60% of questions. 2009 questionnaire with 32 questions showed that percent of correct answers of all students was greater than 90%, in 2010 – greater than 85%. This extraordinary success rate for quite difficult material effectively demonstrate the effectiveness of the laboratory approach.

Regarding 3-hour lab versions and freshmen involvement in the project, the results of summative evaluation using questionnaires with several questions are presented in histograms (Figs. 6-8). Left parts of the figures are for 2008-year and right parts are for 2009-year results. Histograms in Figure 6 show percent of correct answers for Lab 1 and Lab 2 (quantum mechanics course OPT 223 of seniors) after lab completion. Figure 7 shows the same histograms for Monroe Community College students.

Figure 8 shows similar histograms for freshmen course OPT101. Not all participated freshmen answered the questionnaires. Left figure histogram is based on questionnaires contained both scientific questions and evaluation of lecture demonstration.

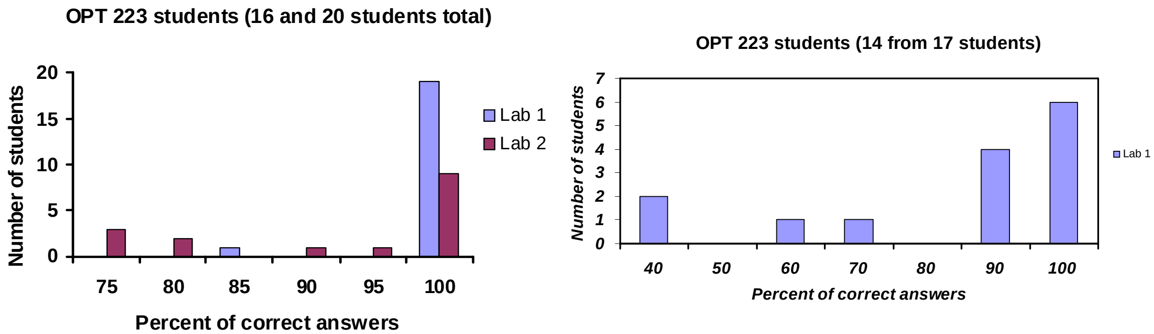

Figure 6. Histograms of evaluation of senior knowledge after lab completion (University of Rochester, Department of Optics, Quantum mechanics course OPT 223): left – for 2008 year, right – for 2009 year.

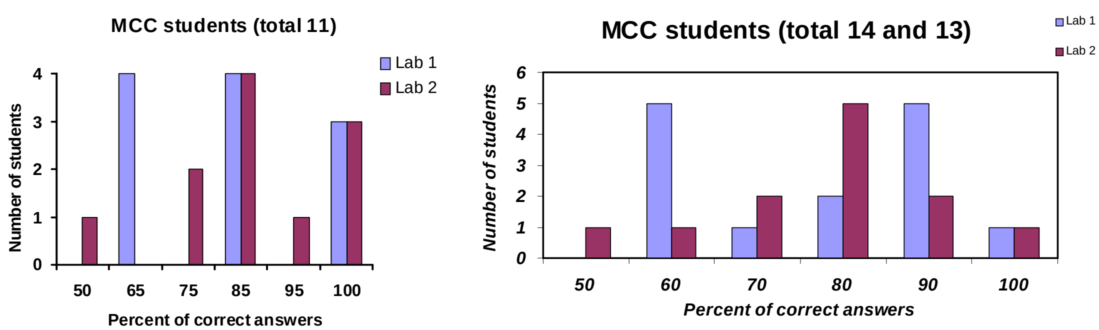

Figure 7. Histograms of evaluation of Rochester Monroe Community College student knowledge after lab completion (Modern Physics course): left – for 2008 year, right – for 2009 year.

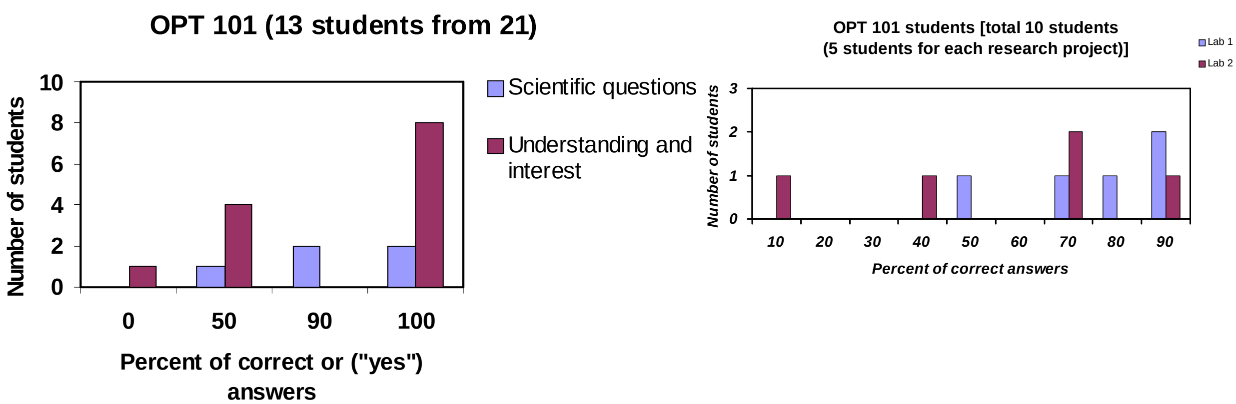

Figure 8. Histograms of evaluation of freshmen knowledge after lecture demonstration (left) and lab completion (right) for University of Rochester, Department of Optics, OPT 101 course: left – for 2008 year, right – for 2009 year. Left figure also shows freshmen evaluation of lecture-demonstration.

A feedback from freshmen after the lab-demonstration-evaluation of 2008 year showed that freshmen need *hands-on experiments* and not only lecture-demonstration. After freshman course evaluation we included in 2009 and 2010 freshman OPT 101 12-hour-research projects. In 2009, 10 freshmen carried out their research projects (see Fig. 8, right), and in 2010 – 16 freshmen.

4. CONCLUSION

The appearance of the new fields of quantum optics, quantum computation, and quantum communications and the rapid progress in photon-counting instrumentation open new opportunities for teaching the most difficult concepts of quantum mechanics by set of simple, easy understandable, and exciting experiments with single and entangled photons. Four labs were prepared at the Institute of Optics, University of Rochester on 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) confocal microscope imaging of single-emitter fluorescence, (4) Hanbury Brown and Twiss setup. Fluorescence antibunching.

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5. ACKNOWLEDGEMENTS

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