Annual Report for Period: 09/2010 - 08/2011

Principal Investigator: Stroud, Carlos R.
Organization: University of Rochester
Submitted By:
Lukishova, Svetlana - Co-Principal Investigator
Title:
Collaborative Research - CCLI Phase II: Diverse Partnership for Teaching Quantum Mechanics and Modern Physics with Photon Counting Instrumentation

### Project Participants

#### Senior Personnel

**Name:** Stroud, Carlos  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**
Carlos Stroud is the project Principal Investigator. He is one of the main persons involved in the project. He teaches the course OPT 223 'Quantum theory of optics' for undergraduate students (seniors). In this course two 3-hour quantum optics laboratories were introduced for each student (four groups of students).

**Name:** D'Alessandris, Paul  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**
Paul D'Alessandris from MCC (Monroe Community College) (Rochester, NY), a co-Principal Investigator, taught Modern Physics course. He jointly with Svetlana Lukishova taught 3-hour quantum optics laboratory for 3 groups of MCC students at the University of Rochester laboratory facility. He developed teaching methods for community college students, collected and evaluated data on students' knowledge after the labs.

**Name:** Lukishova, Svetlana  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**
Svetlana Lukishova is a co-Principal Investigator of the project. She is one of the main persons who constructed teaching instruments and supervised the students in building these instruments as well as their research. She developed teaching strategy, wrote the manuals and evaluated students' knowledge (jointly with internal and external evaluators). Her teaching activities on this project are as follows:
1. Teaching 4-credit hour course 'Quantum Optics and Quantum Information Laboratory';
2. Teaching labs for OPT 223 Quantum Theory of Optics (two three hour labs);
3. Teaching labs for Monro Community College students jointly with their professor P. D'Alessandris (two 3 hour labs)
4. Teaching two lab research project of two groups of freshmen (OPT 101 Optics in Information Age - Prof. Knox).
   She also collaborated with Prof. R. Jodoin (Rochester Institute of Technology) during his sabbatical in her teaching lab.

**Name:** Jodoin, Ronald  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**
Ronald Jodoin (Rochester Institute of Technology, RIT) is a co-Principal Investigator. During the Fall semester he worked on his sabbatical in Svetlana Lukishova's laboratory on entanglement and Bell's inequality setup. He improved alignment of the system and methods of entangled photon registration. His goal is to establish Quantum Optics Teaching Laboratory at RIT.

**Name:** Knox, Wayne  
**Worked for more than 160 Hours:** Yes  
**Contribution to Project:**
Prof. Wayne Knox teaches freshmen course OPT101 Optics in Information Age. After evaluation of students' questionnaires from Phase I grant, he introduced in his course laboratory research projects. Two groups of freshmen carried out their 12-hour research projects in quantum optics labs of Dr. Lukishova.

**Name:** Galvez, Enrico
Worked for more than 160 Hours: Yes
Contribution to Project:
Prof. Enrico Galvez (Colgate University) helped us to evaluate student knowledge.

Name: Belyakov, Vladimir
Worked for more than 160 Hours: Yes
Contribution to Project:
Vladimir Belyakov (Landau Institute for Theoretical Physics, Moscow, Russia) helped us with understanding of beam propagation in chiral photonic bandgap structures which our students prepared during their labs. He also wrote a manuscript for us for easy explanation of beam propagation in such structures.

Name: Zawicki, Joseph
Worked for more than 160 Hours: Yes
Contribution to Project:
Prof. Zawicki (Buffalo State University) participated in this project as an external evaluator. He evaluated our project activity and helped us to process the results of surveys and quizzes.

Post-doc

Graduate Student

Name: Lapin, Zack
Worked for more than 160 Hours: Yes
Contribution to Project:
Graduate student Zack Lapin was a teaching assistant of 4-credit hour laboratory course 'Quantum Optics and Quantum Information Laboratory'. He also developed and maintained a website of the course and helped in evaluation of students' knowledge.

Name: Bissell, Luke
Worked for more than 160 Hours: Yes
Contribution to Project:
Graduate student Luke Bissell developed several elements of experimental setup for single photon source. He also taught students how to prepare samples for single photon source lab.

Name: Gao, Boshen
Worked for more than 160 Hours: Yes
Contribution to Project:
Graduate student Boshen Gao was a teaching assistant of OPT 223 course 'Quantum Theory of Optics'. He also taught one of 3-hour labs attached to the course and helped in evaluation of students' knowledge.

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Colgate University
Prof. Enrico Galvez (Colgate University) helped us to evaluate students' knowledge.

Landau Institute for Theoretical Physics
Prof. V. Belyakov from Landau Institute for Theoretical Physics (Moscow, Russia) worked on beam propagation in chiral photonic bandgap structures which are used in single-photon source lab of Quantum Optics and Quantum Information Laboratory course. He wrote a manuscript for the project how to explain students beam propagation in chiral photonic bandgap structures. He visited labs in Rochester and discussed with Prof. Stroud and Dr. Lukishova his notes written for our project.

Buffalo State College

Other Collaborators or Contacts
Through Optical Society of America we had contacts with several scientists who are interested in the teaching labs, e.g., Prof. Pramode Verma (Williams Chair in Telecom Networking & Director, Telecom. Eng. Program The University of Oklahoma-Tulsa) contacted Dr. Lukishova with invitation to give a seminar about Quantum Optics Labs. In September 2010 Dr. Lukishova delivered the talk at a seminar in Tulsa and discussed with Prof. Verma and his co-workers how to build Quantum Optics Labs in their University. In October 2010 a graduate student of Prof. Verma visited Dr. Lukishova's labs and learned Rochester experience in building such labs.

In August 2011 Dr. Lukishova hosted 6 participants of ALPhA immersion program http://www.advlab.org/imm_singlephotonr2.html.

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)
SEE ATTACHED FILE FOR MAJOR RESEARCH AND EDUCATIONAL ACTIVITIES AND FINDINGS

Findings:
SEE ATTACHED FILE FOR MAJOR RESEARCH AND EDUCATIONAL ACTIVITIES AND FINDINGS

Training and Development:
(1) Students at diverse educational institutions obtained research skills in photon quantum mechanics and modern physics experiments.

(2) Students obtained skills in photon-counting instrumentation that is widely used in quantum information technology and biomedical research;

(3) Students received experience in planning, making decisions and carrying out research experiments in quantum optics;

(4) Students received experience in presentation of their results and explanations of these results to other students

(5) University of Rochester hosted 6 participants of ALPhA Immersion program.

(6) More than 100 students benefited from the project during the second year of funding.
SEE DETAILS IN ACTIVITIES AND FINDINGS FILE

Outreach Activities:
1. Lecture-demonstrations of quantum optics laboratory to 35 Brighton high-school students and teachers (Knox, Lukishova);

2. Lectures (Stroud) on 'Quantum weirdness' in several Universities (Undergraduate colloquium - University of Puget Sound - Sept 2009; Public Lecture - Pacific Lutheran University - Sept 2009; Stookey Award Lecture - Corning, Inc. - Oct 2009; Keynote Address - Annual meeting of New York Science, Engineering and Technology Association; Corning Community College, October 2009; Welcoming Address - Symposium on Quantum Engineering - University of Rochester, Oct. 2009).


4. Physics Colloquium (Stroud): 'Rydberg Electron Wave Packets: Imaging and controlling electrons inside an atom,' Baylor University,
Waco Texas, April 11, 2011. Approximately 60 faculty and students.

5. Evening Public Lecture (Stroud): 'Quantum Weirdness: Technology of the future?' Baylor University, Waco Texas, April 12, 2011. Approximately 150 from University and community.


8. Outreach lecture (Stroud) 'Light Work: Careers in Optics and Lasers,' High school and junior high school students in a local science collaboration, April 22, 2011, Morehead, KY. Approximately 50 students and teachers.

9. Evening Public Lecture (Stroud): 'Quantum Weirdness: Technology of the future?' Morehead State University, Morehead, KY. Approximately 125 from University and community.

10. Schusterman Center Seminar (Lukishova): 'Quantum Optics and Quantum Information Teaching Laboratories at the Institute of Optics, University of Rochester', University of Oklahoma (Tulsa, OK), 14 September 2010. Approximately 30 faculty and students.

11. Seminar (Lukishova): 'Quantum Optics and Quantum Information Teaching Laboratories at the Institute of Optics, University of Rochester', State University of New York at Buffalo (Buffalo, NY), 29 October 2010. Approximately 60 faculty and students.


**Journal Publications**


**Books or Other One-time Publications**

L. Bissell  
(Advisors: C.R. Stroud and S.G. Lukishova)  
Editor(s): University of Rochester  
Collection: Ph.D Thesis Proposal  
Bibliography: University of Rochester, the Institute of Optics
Editor(s): International Conference on Coherent and Nonlinear Optics, Kazan', Russia
Collection: Nanophotonics and Plasmonics
Bibliography: Kazan', Russia, 23-26 August 2010

Editor(s): International Conference on Coherent and Nonlinear Optics, Kazan', Russia
Collection: Nanophotonics and Plasmonics
Bibliography: Kazan', Russia, 23-26 August 2010

Editor(s): Optical Society of America
Bibliography: paper FThQ1

Editor(s): University of Rochester
Bibliography: Ph.D. Thesis

S.G. Lukishova, "Quantum optics laboratory for the undergraduate curriculum: teaching quantum mechanics with photon counting equipment", (2011). Published
Collection: Proceedings of the American Society for Engineering Education (ASEE), St-Lawrence Chapter Annual Conference, 18-19 March 2011, Excelsior College, Albany NY
Bibliography: Invited
http://stl.asee.org/papers_2011/Lukishova.pdf)

Bibliography: paper QThN6

Bibliography: paper JTuI38

Bibliography: paper FThQ1

Bibliography: Physikalisch-Technische Bundesanstalt Braunschweig, Germany
Collection: 4th International Conference on Quantum Information ICQI (6-8 June 2011, Ottawa, Canada), CD-ROM (2011)
Bibliography: 3 pages

S.G. Lukishova, "Liquid crystals under two extremes: (1) high-power laser irradiation, and (2) single-photon level", (2011). Accepted
Bibliography: Invited

S.G. Lukishova, "Liquid crystals under high-power laser irradiation", (2011). Accepted
Bibliography: Invited

Web/Internet Site

URL(s):
http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/
Description:
This site is devoted to Quantum Optics and Quantum Information Laboratory and directly relates to the award. It was started with our Phase I project and maintains by graduate students participating in the project. It contains lab manuals, lectures and presentations, student reports and other relevant materials to the project.

It is linked to the NSF funded educational site www.thequantumexchange.org.

Other Specific Products

Product Type:
Audio or video products
Product Description:
Our students prepared the following videos using low-light level EM-CCD-cameras: (1)on fluorescence of single quantum dots in photonic bandgap hosts, (2) on spontaneous parametric down conversion cones from type I BBO crystals (entangled photon generation).
Sharing Information:
These video are constantly demonstrated during our lectures and outreach talks as well as during quantum optics lab visits by groups of students (university, high-school, community college) and other visitors from different universities and colleges.

Product Type:
Instruments or equipment developed
Product Description:
With participation of undergraduate students (including freshmen) we developed single photon source instrument. As fluorescent emitters we use single NV-color centers in nanodiamonds, single colloidal quantum dots and single dye molecules. We also added spectral diagnostics to this instrument.
Sharing Information:
This instrument is in use by other groups of our University, e.g., by Prof. Boyd and his students. This instrument is in use in different courses of Departments of Optics and Physics (OPT 253/OPT453/PHY434, OPT101, OPT223).

Product Type:
Teaching aids
Product Description:
We created manuals for each quantum optics labs and educational lecture materials on entanglement.
Sharing Information:
All manuals and lecture are placed to the website http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/ linked with NSF supported www.thequantumexchange.com. We have 1693 visitors of our website. Some people ask questions through e-mails.

**Product Type:**
**Teaching aids**

**Product Description:**
Questionnaires for evaluation of students' knowledge on (1) entanglement and Bell's inequalities, (2) single photon interference and (3) single photon sources

**Sharing Information:**
We put questionnaires for different student levels on evaluation of students' knowledge on our website http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/

**Contributions**

### Contributions within Discipline:

1. This project brought state-of-the-art quantum optics and nanotechnology methods and instrumentation to the undergraduate laboratory and classroom of several different institutions (University of Rochester with strong programs on Quantum Mechanics and Quantum Optics and Nanotechnology, Community College and Technical University preparing students for industry).

2. Reducing to practice some of the most abstract components of quantum mechanics by allowing the students to carry out experiments at a range of levels connected with modern applications, in particular, quantum computing and quantum communication.

3. A broad implication and impact on STEM education of students of different levels in different types of educational institutions is the new method of teaching one of the most difficult and abstract concepts of modern physics which promise powerful quantum computers and absolutely secure quantum communication.

### Contributions to Other Disciplines:
Quantum Optics and Quantum Information teaching laboratory which we develop is a multidisciplinary research and teaching laboratory. It includes equipment and tools for quantum optics/quantum information science and technology, optical confocal single-molecule fluorescence microscopy, nanophotonics and nanotechnology and materials' development. Our contributions to other disciplines are as follows:

1. **BIOMEDICINE**
   - Students investigate the new fluorescence markers (e.g., nanodiamonds with color centers, quantum dots (including PbSe quantum dots for 1.3 and 1.5 um spectral regions with a significant penetration depth inside the human body).

2. **NANOPHOTONICS AND NANOTECHNOLOGY**
   - Students develop photonic bandgap structures with tunable bandgaps using liquid crystal materials;
   - Students study different types of nanoemitters.

3. **SINGLE-MOLECULE FLUORESCENCE MICROSCOPY**
   - Students participate in developing the methods of reducing emitter bleaching by special host treatment.

4. **LIQUID CRYSTAL MATERIAL SCIENCE AND TECHNOLOGY**
   - Students learn a new liquid crystal application which may have impact on optical communication technology.

### Contributions to Human Resource Development:
**FIRST YEAR**

1. This project contributed to human resource development in science, engineering and technology by involving students of different levels of different types of educational institutions in building teaching experiments and training them on these setups.

2. During the first year of this project, 7 students were enrolled in a four-credit hour laboratory course which Dr. Lukishova taught during the Fall 2009 semester. Among students participated in this course were two women and one Hispanic student.
(3) 14 students from Monroe Community College carried out this Spring two three hour labs at the University of Rochester. Among them were two minority students and two women.

(4) 17 students of Spring Optics course 'Quantum Mechanics of Optical Materials and Devices' (Stroud), divided by four groups, carried out two 3-hour labs. Among them were three women and one minority student.

(5) 10 freshmen divided in two groups of Optics course 'Optics in Information Age' (Knox) carried out their 12-hour-research projects on single photon source and single photon interference. Among them was one woman.

(6) 25 freshmen of Knox's course 'Optics in Information Age' (four groups) participated in lecture-demonstrations of teaching experiments.

(7) Jodoin from Rochester Institute of Technology (RIT) spent his Fall 2009 sabbatical developing entanglement teaching lab that he will introduce at RIT.

SECOND YEAR

(1) 16 students (three groups) of freshmen OPT 101 course 'Optics in the Information Age' (Knox) carried out 12 hour research projects on single photon source, entanglement and single photon interference. Three graduate students supervised freshmen research projects. Each group delivered a 20-min PowerPoint talk at a final meeting.

(2) 42 students (four groups) of freshmen OPT 101 course 'Optics in the Information Age' (Knox) participated in lecture-demonstrations of four teaching experiments in quantum optics (Lukishova). This demonstration provided students a laboratory experience with the concepts that they studied in the lectures (e.g., single-photon interference, entanglement, fluorescence, etc.)

(3) 14 students (four groups) of the OPT 223 course 'Quantum mechanics of Optical Materials and Devices' (Stroud), carried out one of two 3-hour labs (entanglement and Bell's inequality and single photon interference using Young double slit and Mach-Zehnder interferometer).

(4) 17 students of Monroe Community College of the Modern Physics course (D'Alessandris) carried out two three hour labs (D'Alessandris, Lukishova) at the University of Rochester (entanglement and Bell's inequality and single photon interference using Young double slit and Mach-Zehnder interferometer). Approximately 30% of MCC students are minorities.

(5) 6 students of four-credit hour course OPT253 'Quantum Optics and Quantum Information Laboratory' were trained. A teaching assistant of this course was also trained. In addition, two graduate and one undergraduate student (SUNY Geneseo) carried out research projects on this teaching laboratory facility.

(6) One graduate student of Prof. Verma (University of Oklahoma, Tulsa) was trained on a Rochester lab setup in October 2010. Earlier Dr. Lukishova was invited to Tulsa to share her experience on quantum optics labs with this University.

(7) 5 professors and one graduate student from different universities were trained during 3 days in August 2011 in the ALPhA Immersion program.

**Contributions to Resources for Research and Education:**

One of the goal of this project is involving, consulting and informing others about our results during the course of the project and beyond.

In addition to our website, manuals, lecture materials, questionnaires and video developments reported in Specific Products section, our other contributions for research and educations are as follows:

(1) We interacted with investigators working on similar or related approaches: Prof. E. Galvez (Colgate University), Prof. M. Beck (Whitman College). We sent description of our projects to experts working in science education: Prof. Van Heuvelen, Rutgers University) and Prof. Laird Kramer (Florida International University, Miami.

Teaching laboratory experiments were shown to Prof. V. Belyakov (Landau Institute for Theoretical Physics, Moscow), Prof. A. Aspect (Institute d'Optique, Paris), Prof. F. Capasso (Harvard University) and other visitors of the Institute of Optics.

(2) We published and submitted 12 papers in journals and periodic refereed conference proceedings, 8 papers in one-time refereed conference proceedings.

(3) We delivered invited presentation at the University of Oklahoma (Tulsa) and State University at Buffalo.
(3) Ph.D. Thesis proposal (Bissell) was submitted in 2010 (Lab 3-4) and Ph.D. Thesis (Bissell) was submitted in 2011.

(4) Lecture materials for facilitation of student's understanding are in constant development. All student reports, presentations, lectures, manuals and other teaching materials are placed on a website with approximately 3,000 visitors http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/. Three graduate students participated in this development. This website is linked with the NSF supported Quantum Exchange and ComPadre sites.

(5) Information of Rochester photon quantum mechanic experiments is placed on a website of Advanced Laboratory Physics Association: http://www.advlab.org/imm_singlephotonr2.html In August 2011, UR hosted 6 participants of the ALPhA immersion program for 3 days.

(6) A paper about these teaching experiments was presented in Proceedings of the American Society for Engineering Education (ASEE), St-Lawrence Chapter Annual Conference, 18-19 March 2011, Excelsior College, Albany NY (2011).

Contributions Beyond Science and Engineering:
This project contribute to the public welfare beyond science and engineering. All teaching laboratory experiments are devoted to a pivotal concepts of quantum information that can revolutionize the life of ordinary people. For example, in quantum communication, using single or entangled photons prevent an eavesdropper from being allowed to intercept, without the sender/receiver's knowledge, a message with secret encryption key. Any e-mail message, telephone call, credit card information and other financial transaction will be safe, protected by laws of quantum physics. In addition, powerful quantum computers can solve many unsolvable problems today.

Conference Proceedings

Special Requirements

Special reporting requirements: None
Change in Objectives or Scope: None
Animal, Human Subjects, Biohazards: None

Categories for which nothing is reported:

Any Conference
PROJECT ACTIVITIES AND FINDINGS
Second Year (June 10 – May 11) Award No: 0920500

Collaborative Research – CCLI Phase II: Diverse Partnership for Teaching Quantum Mechanics and Modern Physics with Photon Counting Instrumentation
Carlos R. Stroud and Svetlana G. Lukishova
The Institute of Optics, University of Rochester, Rochester NY 14627
Pail D’Alessandris
Monroe Community College
Ronald Jodoin
Rochester Institute of Technology

1. GOALS AND OBJECTIVES (4-year project)
The central task of this project 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. The project will impact the curricula of three Departments of the University of Rochester (UR), two community colleges (Monroe and Corning), a liberal art college for women, Bryn Mawr, Rochester Institute of Technology, Adelphi University, and other colleges.

The project goals are as follows:
(1) Improvement of student learning at these diverse educational institutions in quantum mechanics and modern physics. The basis for achieving this goal is the experience of the UR (Phase I project) and educational practices from the STEM educational knowledge base on photon quantum mechanics teaching laboratories;
(2) Providing photon-counting instrumentation skills to the future workforce;
(3) Increasing feedback between teaching and learning by involving undergraduate students in planning and decisions during building of the teaching laboratory;
(4) Involvement of undergraduate students in the research process by using research setups and samples in the undergraduate teaching laboratory;
(5) Effective dissemination of project results to the broader education community and contribution to the STEM educational knowledge base.

2. ACTIVITIES
During the second-year period of funding, our main research and education activities have been focused on the following challenges:

- Further developing “mini-labs” [University of Rochester (UR) and Monroe Community College (MCC)]: (1) entanglement lab; (2) single-photon interference lab and two single-photon source labs: (3) single-emitter confocal fluorescence microscopy; (4) fluorescence antibunching, and Hanbury Brown-Twiss interferometer. The labs are prepared to teach additional students who will come to Rochester from Corning Community College and Adelphi University during the third year of funding.

- Rochester Institute of Technology (RIT) established a new program on quantum optics (http://www.rit.edu/news/story.php?id=48438) including quantum optics teaching experiments using the experience gained at the UR. RIT’s quantum optics team includes
Profs. Hach, Adams, Preble and Jodoin, co-PI of the current project (see Fig. 2.1). RIT currently has two quantum optics experiments: (1) single photon interference and (2) characterization of parametric down-conversion and quantum correlation measurements. Bell’s inequality test is in preparation.

Figure 2.1. RIT’s team of the new program on quantum optics.

- Developing and teaching a 4-credit-hour course on Quantum Optics and Quantum Information Laboratory (Lukishova) to six students from two departments. Developing new tests for the evaluation of student knowledge.

- Developing and teaching of two “mini-labs” labs at the UR facilities to 4 groups of 17 students from Monroe Community College (MCC). Entanglement lab was taught by Lukishova (UR), single photon interference lab by D’Alessandris (MCC).

- Developing and teaching one of two “mini-labs” (students’ choice) to 4 groups of 14 seniors of the UR lecture course “Quantum mechanics of optical materials and devices” (Stroud). Entanglement lab was taught by Lukishova, single photon interference lab – by a TA.

- 12-hour freshmen research projects of the “Optics in the Information Age” course (3 groups of 16 students) on room-temperature single photon source, entanglement and single photon interference (Lukishova, Knox and 3 graduate students).

- Two graduate students’ research on room-temperature polarized single photon source (Lukishova). Ph.D of one student of Lukishova/Stroud was submitted to the Thesis Defense Committee.

- Lecture-demonstrations of four quantum optics experiments to 42 students of the course “Optics in the Information Age” (Lukishova, Knox).

- One student from SUNY Geneseo supervised by a UR graduate student carried out his honor senior Thesis at the UR entanglement lab.

- Sharing the photon counting equipment with other research groups, for instance, (i) single-photon EM-CCD-camera, single-photon counting detectors, Newport picometer has been used in students’ research of Boyd’s group on quantum optics.

- Advising University of Oklahoma (Tulsa) in quantum optics teaching experiments. In September 2010, Dr. Lukishova delivered an invited talk at this University. In October 2010, a graduate student from this University visited the UR teaching labs to learn from the UR experience.
Disseminating results by participation of the University of Rochester (Lukishova) in the ALPhA Immersion program supported by the NSF. For 3 days, six participants from different universities learned of the UR experience in quantum optics teaching labs (see Section 5).

Outreach activities (see Section 6).

Dissemination of results by manuscript submissions and conference presentations (see Section 7).

Website development of the course “Quantum Optics and Quantum Information Laboratory (http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab). Linking this website with the NSF supported Quantum Exchange and ComPadre sites. Approximately 3,000 people visited the UR course website.

Evaluation of students’ knowledge by questionnaires, report and essay writing, and oral presentations. Evaluation of students knowledge with the help of the external evaluator Prof. J. Zawicki (Buffalo State University) (see Section 8).

More details of our activities with the main results and findings are described below.

3. FINDINGS

Here are the highlights of findings:

Contribution to knowledge base outcome:

During this year, four teaching experiments in quantum mechanics and modern physics developed by UR, RIT, and MCC for students of diverse educational institutions during this year are modified for dissemination of results to other universities. These experiments are as follows:
- entanglement and Bell’s inequalities;
- single-photon interference in Young’s double-slit and Mach-Zehnder interferometers;
- confocal fluorescence microscopy of single-emitter fluorescence;
- Hanbury Brown and Twiss setup and fluorescence antibunching.

Lecture materials on entanglement and Bell’s inequalities for facilitation of student’s understanding are in constant development. All student reports, presentations, lectures, manuals and other teaching materials are placed on a website with approximately 3,000 visitors http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/. Three graduate students participated in this development. This website is linked with the NSF supported Quantum Exchange and ComPadre sites.

Information of Rochester photon quantum mechanic experiments is placed on a website of Advanced Laboratory Physics Association: http://www.advlab.org/imm_singlephotonr2.html

In August 2011, UR hosted 6 participants of the ALPhA immersion program for 3 days.

Students who participated in this project co-authored two papers, three refereed papers in periodic conference proceedings, and four other refereed conference proceedings.

A paper about these teaching experiments was presented in Proceedings of the American Society for Engineering Education (ASEE), St-Lawrence Chapter Annual Conference, 18-19 March 2011, Excelsior College, Albany NY (2011).
Learning outcome (see Section 8 for details):

- During the second year of the project, nearly 100 students benefited from these teaching experiments (See Section 4). More than 50 students carried out lab experiments, other students participated in lecture demonstrations. Among them are students of three departments of the UR, including 42 freshmen, MCC, and Geneseo College. RIT students started to benefit from this project with a new program on quantum optics as well as from their own quantum optics teaching experiments adopted from the UR.

- Student participants during the Spring 2011 semester were surveyed with respect to their content knowledge as well as their impressions about the activities and about science in general. Both the seniors from the UR (OPT223) and Monroe Community College (PHY262) completed surveys about various aspects of the lab activities and their understanding of the nature of science. 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 lab activities did help students’ understanding, e.g., 24/26 students indicated that the activities aided their understanding or reinforced their previous learning. Only two students (8%) indicated that the activities did not help their learning. The activities also helped to spark student interest. 24/26 or 92% students indicated that they were either more interested in this topic, or that their previous interest in this topic was increased based upon their lab experiences.

- Students were most intrigued by the equipment (set-up, use, alignment); some of the students completing the survey 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, comment such as “The fact that an action in the present can change something (which path the photon took) in the past” are indicative of student’s grappling with these complex quantum issues.

- Freshmen in OPT101 completed pre-lab, lab and post-lab questions. Student gains from pre-lab through post-lab responses are substantial. Students demonstrated substantial gains between their pre-lab and their post-lab responses. In this course, students created (PowerPoint) presentations of their research over the course of a semester; the progress of the students was remarkable.

- In order to demonstrate more effectively the impact of the lab experiences upon student learning, during the 2011-2012 academic year we will calculate individual item difficulties, discrimination and response pattern data for each assessment item. Additionally, we will use the open-ended responses from previously obtained student papers to develop either multiple choice or other response formats for some of the items on either course or program assessments. The combination of multiple choice (or alternative format) items, along with some open-ended responses, will more adequately address both reporting needs and will facilitate further program refinement.

Community building outcome:

- Three Rochester educational institutions (UR, MCC, RIT) collaborate and share their experience on improvement of student learning in quantum mechanics and modern physics at these diverse educational institutions (See Sections 3 - 6).
Our website of Quantum Optics and Quantum Information Laboratory has already had nearly 3,000 visitors.

Prof. Stroud and Dr. Lukishova delivered invited lectures in different educational institutions (see Section 6).

Dr. Lukishova participated in the ALPhA immersion program (see Section 5).

Sharing the experience with the University of Oklahoma (Tulsa) by visiting this University and training the UO graduate student at the UR facility.

Dr. Lukishova delivered an invited talk and shared the UR experience at the educational conference of the American Society for Engineering Education (ASEE), St-Lawrence Chapter Annual Conference, 18-19 March 2011, Excelsior College, Albany NY.

Below is a more detailed description of some, above-mentioned findings. This second year of the project was devoted to establishing quantum optics program at RIT using the experience of UR, further developing and teaching 3 hour versions of four teaching labs (“mini-labs”) for UR and MCC students, preparing lecture materials for the labs, teaching the 4-credit hour course, freshmen research projects, lecture-demonstrations to freshmen, dissemination of Rochester results among 6 participants of the ALPhA Immersion program and among faculty of the University of Oklahoma (Tulsa), data collection for evaluation of students’ knowledge and the evaluation of the project by the external evaluator. We also participated in intensive outreach activity delivering lectures in different educational institutions.

3. DEVELOPMENT OF TEACHING EXPERIMENTS WITH STUDENTS’ PARTICIPATION

Rochester Institute of Technology (RIT) established its own program in quantum optics using the UR experience. Profs Preble and Jodoin visited the UR and learned how to align the entanglement set up (Fig. 3.1). Profs. Hach and Jodoin in the Physics Department, and Prof. Preble in the Microsystems Engineering Program delivered a course entitled Quantum Optics during the spring quarter of the 2010 – 2011 school year at RIT. Prof. Hach gave the lecture part of the course and Profs. Jodoin and Preble did the lab. RIT participants renovated a laboratory space during the winter quarter and purchased the equipment that they needed jointly through the Physics Department and Microsystems Engineering. This included an optical isolation table, blue diode laser, two avalanche photodiode single photon counting modules, and a pair of BBO crystals for spontaneous parametric down conversion. The remaining equipment was already available. The laboratory experiments that RIT students were able to do included single photon interference, the quantum eraser, and detection of entangled photons. Three undergraduate physics majors and one graduate student in Microsystems Engineering took the course.

Since the course ended in May RIT participants have purchased four more photon counting modules. A physics major has begun working with Preble on the Hanbury Brown-Twiss effect as his senior capstone project, which will conclude next winter. Next spring the quantum optics course will be offered again, and new experiments will be added to the laboratory component, for instance, a Bell’s inequality test.
To reduce the time of the experiments, the UR made some modifications in all labs. Student Justin Winkler wrote a LabView-based software for data acquisition from the single-photon counting avalanche photodiode modules during the rotation of a motorized mount with a linear polarizer in front of one of the detectors (Fig. 3.2). Another version of a LabView-based software for the EM-CCD-camera permitted to carry out the polarization measurements with a polarizer rotation from 0 to 360° (using a motorized rotation stage) on a single-photon source setup within 3-5 min instead of 2 hours. Collaboration with Boyd’s group (University of Ottawa) with participation of the UR students permitted to develop a LabView-based software for the EM-CCD-camera with possibility to store and summarize 100 images. It will be used in the single-photon interference experiments.

4. PROVIDED OPPORTUNITIES FOR TRAINING AND DEVELOPMENT

More than 100 students benefited from the project during the second year of funding. The groups of trained students with different level are listed below:

(1) 16 students (three groups) of freshmen OPT 101 course “Optics in the Information Age” (Knox) carried out 12 hour research projects on single photon source, entanglement and single photon interference. Three graduate students supervised freshmen research projects. Each group delivered a 20-min PowerPoint talk at a final meeting.

(2) 42 students (four groups) of freshmen OPT 101 course “Optics in the Information Age” (Knox) participated in lecture-demonstrations of four teaching experiments in quantum optics (Lukishova). This demonstration provided students a laboratory experience with the concepts that they studied in the lectures (e.g., single-
photon interference, entanglement, fluorescence, etc.)

(3) 14 students (four groups) of the OPT 223 course “Quantum mechanics of Optical Materials and Devices” (Stroud), carried out one of two 3-hour labs (entanglement and Bell’s inequality and single photon interference using Young double slit and Mach-Zehnder interferometer).

(4) 17 students of Monroe Community College of the Modern Physics course (D’Alessandris) carried out two three hour labs (D’Alessandris, Lukishova) at the University of Rochester (entanglement and Bell’s inequality and single photon interference using Young double slit and Mach-Zehnder interferometer). Approximately 30% of MCC students are minorities.

(5) 6 students of four-credit hour course OPT253 “Quantum Optics and Quantum Information Laboratory” were trained. A teaching assistant of this course was also trained. In addition, two graduate and one undergraduate student (SUNY Geneseo) carried out research projects on this teaching laboratory facility.

(6) One graduate student of Prof. Verma (University of Oklahoma, Tulsa) was trained on a Rochester lab setup in October 2010. Earlier Dr. Lukishova was invited to Tulsa to share her experience on quantum optics labs with this University.

(7) 5 professors and one graduate student from different universities were trained during 3 days in August 2011 in the ALPhA Immersion program (see the next section 4).
5. PARTICIPATION OF THE UNIVERSITY OF ROCHESTER IN THE ALPHA IMMERSION PROGRAM

The Advanced Laboratory Physics Association (ALPhA) (http://www.advlab.org) is an association of college and university faculty and staff dedicated to advanced experimental physics instruction. ALPhA’s Laboratory Immersion Program (http://www.advlab.org/immersions.html) provides participants with two to three days of intensive hands-on work with advanced laboratory experiments. This program leaders negotiated with Perkin-Elmer company resulting in the possibility to buy the single-photon-counting detectors for educational purposes with higher dark count, but at half the cost for research set ups (http://www.advlab.org/spqm.html). Many Universities will now be able to build labs on photon quantum mechanics experiments. On 18-20 August 2011, Dr. Lukishova was the mentor of six ALPhA Immersion Program participants who came to Rochester to learn how to build entanglement and Bell’s inequalities lab, single-photon source lab and single-photon interference lab. The following professors learned from the Rochester experience: 1. Prof. Michael Braunstein (Central Washington University), 2. Prof. James Buchholz (California Baptist University and University of California, Riverside), 3. Prof. Thushara Perera (Illinois Wesleyan University), 4. Daniel Dominguez, graduate student responsible for teaching labs (Texas Tech University), 5. Prof. Matthew C. Sullivan (Ithaca College), 6. Prof. Walter F Smith (Haverford College).

Figure 4.1. Rochester ALPhA Immersion program participants.

6. OUTREACH ACTIVITIES


6. Outreach lecture (Stroud) “Light Work: Careers in Optics and Lasers,” High school and junior high school students in a local science collaboration, April 22, 2011, Morehead, KY. Approximately 50 students and teachers.

7. Evening Public Lecture (Stroud): “Quantum Weirdness: Technology of the future?” April 22, 2011, Morehead State University, Morehead, KY. Approximately 125 from University and community.

8. Schusterman Center Seminar (Lukishova): “Quantum Optics and Quantum Information Teaching Laboratories at the Institute of Optics, University of Rochester”, University of Oklahoma (Tulsa, OK), 14 September 2010. Approximately 30 faculty and students.

9. Seminar (Lukishova): “Quantum Optics and Quantum Information Teaching Laboratories at the Institute of Optics, University of Rochester”, State University of New York at Buffalo (Buffalo, NY), 29 October 2010. Approximately 60 faculty and students.


Figure 3.1. Left - Seminar at the University of Oklahoma (Tulsa); Right – Lecture at HTB (Salzburg).
7. PUBLICATIONS AND PRESENTATIONS (second year of the project)

5.1. Journal publications and periodically published conference proceedings


5.2. One-time publications in conference proceedings


5.3. Website:

http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/

8A. EVALUATION OF STUDENT KNOWLEDGE WITH THE HELP OF EXTERNAL EVALUATOR

External evaluation of both student learning and our project success was made by Prof. Joseph Zawicki, Buffalo State University (http://faculty.buffalostate.edu/zawickjl). Some of his current research interests are relationships between prior knowledge and learning in science and performance assessment tasks in optics.

Prof. Zawicki visited the University of Rochester several times and discussed with a PI (Stroud) and a co-PI (Lukishova) the assessment methods for each student level. During these discussions several surveys has been created. Both Fall and Spring students with a diverse background answered questions of different surveys.

Prof. Zawicki helped in processing of collected data and its organization. Section 8B is the result of his work using data collected by the UR and MCC. His main suggestion is that the Quantum Optics Lab has successfully completed the 2010-2011 academic year and introduced students to hands-on bench work on photon quantum mechanics. Student reports, presentations and responses to specific assessment questions provide evidence of the level of impact of this program.

In order to more effectively demonstrate this impact in subsequent years, he recommended that individual item difficulties, discrimination and response pattern data be calculated for each assessment item. He also suggested to develop either multiple choice or other response formats for some of the items on either course or program assessments. The combination of multiple choice (or alternative format) items, along with some open-ended responses, will more adequately address both reporting needs and will facilitate further program refinement.
8B. EVALUATION OF STUDENT KNOWLEDGE (in collaboration with external evaluator Prof. Zawicki)

Over the course of the past year 52 students, largely at the undergraduate level, completed either course-based laboratory activities or conducted research using the Quantum Optics Laboratory. Students from the University of Rochester, Monroe Community College and SUNY Geneseo participated in various activities, as shown in Table 1. One senior student took advantage of the optics lab facilities to complete his Honor’s thesis.

Table 8.1. Student Participation, by course and by campus, for the 2010-2011 Academic Year.

<table>
<thead>
<tr>
<th>Course/Campus</th>
<th>Students (N)</th>
<th>Experiences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fall 2010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OPT253</td>
<td>6</td>
<td>Quantum Optics and Quantum Information Laboratory. Students met in three hour sessions, twice per week (90 Contact Hours).</td>
</tr>
<tr>
<td>OPT101</td>
<td>16</td>
<td>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</td>
</tr>
<tr>
<td>Spring 2011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OPT223</td>
<td>14</td>
<td>Quantum Mechanics for Optical Materials and Devices. Students completed a lab activity integrated into the course curriculum – Single Photon Interference and Entanglement and Bell’s Inequalities labs.</td>
</tr>
<tr>
<td>PHY262 (MCC)</td>
<td>17</td>
<td>Modern Physics Course. Students from Monroe Community College participated in two lab activities – Entanglement and Bell’s Inequalities, and Single Photon Interference.</td>
</tr>
<tr>
<td>SUNY Geneseo</td>
<td>1</td>
<td>A senior student from SUNY Geneseo completed a Honor thesis on entanglement using the optics lab at the University of Rochester.</td>
</tr>
</tbody>
</table>

¹ A total of 42 students enrolled in this campus wide program. 16/42 students (~40% of the course enrollment) opted to participate in the research projects supported by this project.

Fall 2010
16 students in OPT101, a freshman research course, opted to participate in one of three projects that involved either photon entanglement, single photon sources or a dual slit interference lab. 6 students in OPT253, Quantum Optics and Quantum Information Laboratory, completed numerous lab activities over the course of the semester. The course met two times weekly, for a three hour period each time. Teams of graduate students assisted Dr. Lukishova and the students during these experiences.

Spring 2011
14 students in OPT223, Quantum Mechanics for Optical Materials and Devices, completed a single lab on Entanglement and Bell’s Inequalities or Single-Photon Interference. Additionally, 17 students from the Modern Physics (PHY262) course at Monroe Community College participated in two activities – both an entanglement lab mentioned and the single photon interference mentioned previously. A senior student from SUNY Geneseo was also able to use the lab for Honor’s thesis research.

In each case, the lab activities are integrated into the course content and the participation times for the students in OPT253, OPT223 and PHY262 (MCC), were scheduled beyond the normally scheduled class meeting hours. Copies of the lab activities are appended to this report.

Evaluation
Student participants during the Spring 2011 semester were surveyed with respect to their content knowledge as well as their impressions about the activities and about science in general. The survey results are presented below.

Laboratory Evidence
Student participants in PHY262, a course offered through Monroe Community College, 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 Figure 8.1.
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 had the greatest difficulty 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. In the future, facilitating greater discussion about the connection between the experimental procedures and the evidence that is collected may be an effective manner of addressing this issue.

Students in OPT101 completed pre-lab, lab and post-lab questions. The grades for five students are shown in Table 1. Student gains from pre-lab through post-lab responses are substantial. Students demonstrated substantial gains between their pre-lab and their post-lab responses. In this course, students created (PowerPoint) presentations of their research over the course of a semester; the progress of the students was remarkable.

In order to more effectively demonstrate the impact of the lab experiences upon student learning, during the 2011-2012 academic year the researchers will calculate individual item difficulties, discrimination and response pattern data for each assessment item. Additionally, the researchers will use the open-ended responses from previously obtained student papers to develop either multiple choice or other response formats for some of the items on either course or program assessments.

Students in OPT223 completed one lab report by each group of 3-4 students, but they were offered to select this lab from two labs, so some students submitted the reports of lab 1, the other students – the reports of lab 2. Student scores on the six items addressed in each report are shown in Figures 2 and 3. 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 at largely
correct answers to the questions posed in lab #2.

Content Knowledge
A content “quiz,” consisting of nine items, was completed by the students in the Fall 2010 OPT253 course. The
items, as well as the correct, partially correct, and incorrect responses, and the overall item difficulties, are presented
in Table 8.2. The course instructor assigned partial credit for some items (#1 and #6). Question 1 earned partial
credit if the student talked about complementarity in general or in the abstract; question 6 earned partial credit if the
student merely stated that bullets have large mass, or are "big", without mentioning that this creates an incredibly
small wavelength, etc. Questions 1 & 6 were the most difficult items on this quiz. With the exception of two items
(2 & 7), the remaining items, comprising the bulk of the survey, had difficulty levels above mastery (85%). The data
support the conclusion that the students competing these activities understood these activities well.

Table 8.2. Student content knowledge survey analysis.

<table>
<thead>
<tr>
<th>Item</th>
<th>Correct</th>
<th>Partially Correct</th>
<th>Incorrect</th>
<th>Difficulty</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Explain complementarity (wave-particle duality) of photons in your experiment.</td>
<td>9</td>
<td>4</td>
<td>4</td>
<td>65%</td>
</tr>
<tr>
<td>2. Draw the interference pattern from a single- and double-slit.</td>
<td>13</td>
<td>0</td>
<td>4</td>
<td>76%</td>
</tr>
<tr>
<td>3. Sketch (on the figure below) the intensity pattern on the screen you would see if one slit was blocked.</td>
<td>16</td>
<td>0</td>
<td>1</td>
<td>94%</td>
</tr>
<tr>
<td>4. Sketch…if both slits were open. Sketch… of bullets if one slit was blocked.</td>
<td>16</td>
<td>0</td>
<td>1</td>
<td>94%</td>
</tr>
<tr>
<td>5. Sketch…the accumulation pattern of bullets…if both the slits were open.</td>
<td>15</td>
<td>0</td>
<td>2</td>
<td>88%</td>
</tr>
<tr>
<td>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.</td>
<td>8</td>
<td>6</td>
<td>3</td>
<td>65%</td>
</tr>
<tr>
<td>7. Draw the schematics of a Mach-Zehnder interferometer.</td>
<td>13</td>
<td>1</td>
<td>3</td>
<td>79%</td>
</tr>
<tr>
<td>8. Will you observe single-photon interference at the output of a Mach-Zehnder interferometer if you will know in which arm of this interferometer photons can be horizontally and vertically polarized?</td>
<td>14</td>
<td>3</td>
<td>0</td>
<td>91%</td>
</tr>
<tr>
<td>9. How many photon/s with a wavelength of 633 nm do you have at laser power 1 mW?</td>
<td>14</td>
<td>3</td>
<td>0</td>
<td>91%</td>
</tr>
</tbody>
</table>
Both the undergraduate students from the University of Rochester (OPT223) and Monroe Community College (PHY262) completed surveys about various aspects of the lab activities and their understanding of the nature of science.

Figure 8.4 provides data indicating that a number of students (14) were most intrigued by the equipment (set-up, use, alignment); approximately 11 of the students completing the survey 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, comment such as “The fact that an action in the present can change something (which path the photon took) in the past” are indicative of student’s grappling with these complex quantum issues.

Figure 8.5 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 “sections” – they felt that there were too many students in their groups or larger rooms. Recording their data readings did not enamor students – they would, in general like to have this task done automatically. Four students commented that they would have liked to been allowed to align the equipment themselves.

Student responses to the most challenging aspects of the activities are summarized in Figure 8.6. Seven students commented on using the equipment (they wished to align it themselves, difficulty taking readings), two students commented on the difficulty of observing fringes, and five students commented on how challenging it was to generate 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 bracket notation used in the quantum entanglement lab” are fairly representative of the general comments students provided.
The data from student comments about changes that could be made to improve the activities are presented in Figure 8.7.

Students were generally positive – often suggesting that the labs are fine as they are. The comments that were made suggested either the use of additional visualizations or simulations. While some students wished to have less direct instruction, some students asked for additional instruction about particular topics. The number of comments in this section was quite modest. The authors suspect that the large number of “No Response” 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 their previous learning. Only two students (8%) indicated that the activities did not help their learning. The activities also helped to spark student interest. Twenty-four students (24/26 or 92%) indicated that they were either more interested in this topic, or that their previous interest in this topic was supported increased based upon their lab experiences. A summary of the student responses is presented in Figures 8.8 and 8.9.

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. Two student comments were disconcerting – “Yes, scientist(s) tend to make up things they don't know,” and “Yes, planning and designing, but also after data collection. If the data is inconclusive then the planning and designing creativity may need to take place again. Also, you could say during data collection as long as you don't fudge data.” The creativity data is in presented in Figure 8.10, and the the overall impact of the lab activities is summarized in Table 8.3.

![Figure 8.7. Changes to improve?](image)

![Figure 8.8. Help to understand?](image)

![Figure 8.9. Increase your Interest?](image)

![Figure 8.10. Creativity & Imagination?](image)
Table 8.3. Student responses to survey items related to understanding, interest and the nature of science.

<table>
<thead>
<tr>
<th>Assessment Item</th>
<th>Yes</th>
<th>Somewhat</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Did the lab(s) help you to understand...</td>
<td>22</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Did the lab(s) increase your interest?</td>
<td>20</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Does Science Require Experiments?</td>
<td>17</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Some of the suggestions made by students are feasible others are not. Optics lab space with the building and on the University campus is limited. The current facilities are reasonable and unlikely to change for the time being. Additionally, the faculty and graduate teaching assists are being used as effectively as possible. While consideration may be given to scheduling additional lab sections, financial as well as time constraints may very well rule out this option.

The program will continue to survey participants, and will consider the student responses as courses are refined in the future. The program will continue to refine the formative and summative instruments that have been used to date.

Conclusions & Recommendations

The Optics Lab has successfully completed the 2010-2011 academic year and introduced 52 students to hands-on bench work involving photon quantum mechanics and modern physics experiments. Student reports, presentations and responses to specific assessment questions provide evidence of the level of impact of this program.

In order to more effectively demonstrate this impact in subsequent years, it is recommended that individual item difficulties, discrimination and response pattern data be calculated for each assessment item. Additionally, the researchers will use the open-ended responses from previously obtained student papers to develop either multiple choice or other response formats for some of the items on either course or program assessments. The combination of multiple choice (or alternative format) items, along with some open-ended responses, will more adequately address both reporting needs and will facilitate further program refinement.
Project Activities and Findings

First Year (June 09 – May 10) Award No: 0920500

Collaborative Research – CCLI Phase II: Diverse Partnership for Teaching Quantum Mechanics and Modern Physics with Photon Counting Instrumentation

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Pail D’Alessandris
Monroe Community College
Ronald Jodoin
Rochester Institute of Technology

Goals and Objectives (4-year project)
The central task of this project 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. The project will impact the curricula of three Departments of the University of Rochester (UR), two community colleges (Monroe and Corning), liberal art college for women, Bryn Mawr, Rochester Institute of Technology, Adelphi University, and two other colleges that will be identified after a 4th year workshop. The project goals are as follows:

(1) Improvement of student learning at these diverse educational institutions in quantum mechanics and modern physics. The basis for achieving this goal is the experience of the UR (Phase I project) and educational practices from the STEM educational knowledge base on photon quantum mechanics teaching laboratories;

(2) Providing photon-counting instrumentation skills to the future workforce;

(3) Increasing feedback between teaching and learning by involving undergraduate students in planning and decisions during building the teaching laboratory;

(4) Involvement of undergraduate students in the research process by using research setups and samples in the undergraduate teaching laboratory;

(5) Effective dissemination of project results to the broader education community and contribution to the STEM educational knowledge base.

During the first year period of funding three institutions worked on the initial tasks of the project: University of Rochester, Rochester Institute of Technology and Monroe Community College. Our main research and education activities have been focused on the following challenges:

- Developing “mini-labs” (three-hour versions for teaching experiments built during the Phase I project): (1) entanglement lab; (2) single-photon interference lab; single photon source labs: (3) single emitter confocal fluorescence microscopy; (4) fluorescence antibunching, and Hanbury Brown-Twiss interferometer.

- Developing independent program of quantum optics teaching experiments at the Rochester Institute of Technology (RIT) using the experience gained at the UR. Prof. Jodoin, co-PI of the project, spent his Fall 2009 sabbatical at the UR working with Dr. Lukishova on one of the versions of the entanglement lab which can be implemented at RIT, as well as on single
photon interference lab. Under the mentoring of Lukishova Jodoin performed existing experiments on single photon interference and a test of Bell’s inequality using quantum entanglement. With this background and experience he worked on a new setup to do quantum entanglement using a blue diode laser as the source for parametric down-conversion. This involved aligning the optics and assembling and testing a new coincidence counter that interfaced to a computer using LabView.

- As an additional educational experience for RIT, Jodoin audited Stroud’s course on quantum optics and attended several colloquia hosted by the Institute of Optics.
- Jodoin is currently developing the laboratory portion of a new quantum optics course at RIT. His colleague in the Physics Department, Edwin Hach, is designing the lecture part of the course. They are collaborating with Stefan Preble in the Microsystems Engineering Program, who is supplying some of the needed equipment. For the RIT laboratories Jodoin has designed four experiments based on those that he did at the Institute of Optics (UR). They are (1) single photon interference, (2) the quantum eraser, (3) characterization of parametric down-conversion, and (4) a test of Bell’s inequality. The equipment is currently in house or being purchased so that the course can be offered next academic year.
- To prepare typical physics undergraduates at RIT for the experiments, Jodoin has written a comprehensive set of pre-laboratory notes. These include the history and significance of the experiments and mathematical derivations of the results expected from quantum theory.
- Developing lecture materials on entanglement and Bell’s inequalities to facilitate students’ understanding of labs [Lukishova, Jodoin, Stroud in collaboration with Eberly (Department of Physics, UR)];
- Developing and teaching 4-credit-hour course on Quantum Optics and Quantum Information Laboratory (Lukishova) to seven students from three departments;
- Preparation and teaching of two “mini-labs” labs at the UR facilities to 3 groups of 14 students of Monroe Community College (MCC). Entanglement lab was taught by Lukishova (UR), single photon interference lab – by D’Alessandris (MCC).
- Preparation and teaching two “mini-labs” to 4 groups of 17 seniors of the UR lecture course “Quantum mechanics of optical materials and devices” (Stroud). Entanglement lab was taught by Lukishova, single photon interference lab – by a TA.
- 12-hour freshmen research projects on “Optics in the Information Age” course (2 groups of 10 students) on room-temperature single photon source and single photon interference (Lukishova, Knox);
- Students’ research on room-temperature polarized single photon source (Lukishova)
- Lecture-demonstrations of four quantum optics experiments to 25 students of the course “Optics in the Information Age” (Lukishova, Knox);
- Lecture-demonstrations of quantum optics experiments to 3 groups of 35 high-school students and their teachers;
- Sharing the new equipment with other research groups, for instance, (i) single-photon EM-CCD-camera, Newport picometer has been used in students’ research of Boyd’s group on
quantum optics. Boyd’s students carried out a research project using the confocal microscope setup with antibunching measurements (Labs 3-4). Novotny’s students used the entanglement setup and EM-CCD-camera for their research project.

- Evaluation of students’ knowledge by questionnaires, report and essay writing, and oral presentations. Evaluation of the first step of the project by the internal evaluator;
- Dissemination of results by writing papers and conference paper submission;
- Website preparation of the course “Quantum Optics and Quantum Information Laboratory (http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab). Linking this website with NSF supported the Quantum Exchange and ComPadre sites.
- Dissemination of results by demonstration of teaching experiments to Prof. E. Galvez (Colgate University), professors Capasso (Harvard University), Aspect (Institute D’Optique, France), Belyakov (Landau Institute for Theoretical Physics, Russia), and other visitors of the Institute of Optics (UR);
- In addition to current rooms for teaching labs (210 sq. feet, 175.4 sq. feet and 242 sq. feet), the Institute of Optics provided an office room (175.4 sq. feet) which was used by visitors and collaborators.
- Outreach activities (see details below).

More details of our activities with the main results and findings are described below.

Here are the highlights of these findings:

Contribution to knowledge base outcome:
- Four teaching experiments in quantum mechanics and modern physics are in development by UR, RIT and MCC for students of diverse educational institutions. (Lukishova, Stroud, Jodoin, D’Alessandris, graduate student Bissell, undergraduate students):
  - entanglement and Bell’s inequalities;
  - single-photon source interference in Young’s double-slit and Mach-Zehnder interferometers;
  - confocal fluorescence microscopy of single-emitter fluorescence;
  - Hanbury Brown and Twiss setup and fluorescence antibunching.
- Manuals were written for four experiments with photon counting instrumentation.
- Lecture materials on entanglement and Bell’s inequalities for facilitation of student’s understanding were prepared after intensive discussions with leading quantum optics scientists and teachers.
- Students participated in this project co-authored one published paper, two accepted papers, three accepted conference summaries.

Learning outcome:
- During this first year of the project more than 100 students benefited from these teaching experiments. Among them are students of three departments of the UR, including 25 freshmen, MCC, RIT as well as students and teachers from Brighton High School.
• Using questionnaires on photon quantum mechanics showed that 63% of OPT 223 students (UR) answered correctly 90% of questions, 60% of MCC students answered correctly 80% of questions and 60% of freshmen of OPT 101 (UR) participating in research answered correctly 70% of questions.

• Students’ mastery in photon-counting instrumentation of 4-credit hour course with 15-hour labs is shown in that 60% of students received total scores of “A” and the rest of students received total scores of “A-“. The grades were based on students’ capability of carrying out the experiments, writing the reports and delivering oral presentations. All students answered correctly 90% of questions.

Community building outcome:

• Three Rochester educational institutions (UR, MCC, RIT) collaborate and share their experience on improvement of student learning at these diverse educational institutions in quantum mechanics and modern physics.

• We interacted with investigators of other universities and counties working on similar or related approaches: Galvez (Colgate University), Beck (Whitman College), Bentley (Adelphi University), Noel (Bryn Mawr College).

• Teaching experiments were shown to Capasso (Harvard University), Aspect (Institute d’Optique, France), Belyakov (Landau Institute for Theoretical Physics (Russia), and other visitors of the Institute of Optics.

• Our website of Quantum Optics and Quantum Information Laboratory has already more than 1,700 visitors. Some people contact us directly by e-mails.

• Prof. Stroud delivered invited lecture in Pennsylvania, Lukishova was invited to deliver her lecture in Oklahoma this September.

Below is a more detailed description of some above-mentioned findings. This first year of the project was devoted to developing of quantum optics teaching experiments at RIT using the experience of UR, developing and teaching 3 hour versions of four teaching labs (“mini-labs”) for UR and MCC, preparing lecture materials for the labs, teaching the 4-credit hour course, lecture-demonstrations to students of different experience including freshmen and high-school students, work on a mobile single-photon source device, starting data collection for evaluation of students’ knowledge and the first evaluation of the project by the internal evaluator.

1. DESCRIPTION OF TEACHING EXPERIMENTS WITH EXPERIMENTAL RESULTS PERFORMED BY STUDENTS OF DIFFERENT LEVELS

Lab. 1. Entanglement and Bell’s inequalities

The schematic of the teaching experiment on polarization-entangled photons and Bell’s inequalities is shown in the Figure 1, left. We used P. Kwiat approach [Phys. Rev A. 60, R773 (1999)]. Light from the laser passes through a pair of type I BBO crystals that are mounted back-to-back with one rotated 90° 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 A and B). These two APDs are located on two diametrically opposite points of the down-converted cone. In this arrangement each crystal can support downconversion of one pump polarization (H or V). A 45° polarized pump photon can be downconverted in either crystal, producing a polarization entangled pair of photons:
\[|H\rangle + |V\rangle \rightarrow |V', V\rangle + \exp(i\Delta)|H, H\rangle.\] Quartz plate rotation compensates phase \(\Delta\) introduced by the crystals. Coincidences are detected by a fast logic circuit (counter) card inside a PC. Figure 1, right (obtained by the students of 3-hour-lab version) 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 of the linear polarizer A varies at two different fixed angles \(\beta\) of the polarizer B. Calculation of Bell’s inequality in the Clauser-Horn-Shimony-Holt form shows its violation \((S > 2)\).

![Figure 1. Entanglement and Bell’s inequalities lab: left – schematics of the experiment (interference filters transmitted only downconverted light 727.6 nm are placed in front of each detector); right – coincidence count dependence on relative polarizer angle in front of detectors A and B. High fringe visibility (greater than 0.71) indicates Bell’s inequality violation and entanglement.](image)

UR has two experimental setups located in different rooms with different lasers and different BBO crystal sets. One setup (Figure 2) was used for teaching experiments, another (Figure 3) – for modeling of the RIT version of this lab. For UR teaching labs we use an 100 mW, 363.8 nm, cw argon ion laser donated by Spectra Physics division of Newport Corporation. The results on this setup are very reproducible and we used it for quick demonstration of photon entanglement during only 2-3 hours of “mini-lab” for several groups of students of different levels (UR and MCC).

![Figure 2. Entanglement lab setup with an argon ion laser (left) and its entangled photon registration module (right).](image)

This setup also permits students to observe and prepare video files of the cone of downconverted photons using a low-light level EM-CCD camera.

The second setup with 10 mW, 406 nm excitation (diode laser) is shown in Figure 3. This setup was described in papers of D. Dehlinger and M.W. Mitchell [Am. J. Phys., 70, 898 and 903 (2002)]. Jodoin (RIT) during his sabbatical at the UR and Lukishova worked on developing
an easier method of alignment of this setup as well as on the use of a cheap computer board for coincidence count measurements.

Figure 3. Part of entanglement lab setup with a diode laser excitation (left) (APDs and polarizers are not shown) and its entangled photon registration module with APDs and polarizers (right).

**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 are made using a He-Ne laser beam, attenuated to the single photon level and an EM-CCD camera (Figure 4, left). Mach-Zehnder interferometer (Figure 4, right) is used for the demonstration of a single-photon interference after removing “which-way” information (identification of the path). Figure 5 shows photographs of experimental setup (left) and one of three groups of Monroe Community College students carrying out this experiment.

Figure 4. Left: Single-photon interference using Young’s double-slit at different exposure time. Right: Mach-Zehnder interferometer schematics for “which-way experiment

Figure 5. Photograph of single-photon interference setup with low-light level EM-CCD-camera (left); group of MCC students (right) carrying out this experiment.
Lab 3. Single photon source I: Confocal microscope imaging of single-emitter fluorescence
This Lab and the next, Lab 4, are devoted to a single-photon source (SPS) with photons separated in time (antibunching). To produce single photons, excited laser beam should be focused on a single emitter which produces single photon at a time. SPS is the key hardware element of quantum cryptography. At the same time methods and instrumentation of confocal fluorescence microscopy are widely used in nanotechnology, biology and biomedicine.

Laser excitation at 532-nm (8 ps pulse duration, 76 MHz pulse repetition rate) as well as at 514 nm (cw) was used for confocal microscope single-emitter fluorescence imaging in the teaching labs (Figure 6). Colloidal semiconductor quantum dots and single color-centers in nanodiamonds were used as single emitters.

Students enrolled in the laboratory course also participated in research. They carried out imaging of single emitter fluorescence in photonic bandgap cholesteric liquid crystal hosts and photon antibunching measurements, observed “blinking” of quantum dots using raster scan or wide-field microscopy with EM-CCD camera.

Figure 6. Left: Photograph of a confocal fluorescence microscope for SPS applications; Right: Freshmen work on 12-hour research project of “Optics for information age” course (Fall 2009).

Lab. 4. Single Photon Source II: Hanbury Brown and Twiss setup. Fluorescence antibunching
Hanbury Brown and Twiss interferometer for fluorescence antibunching measurements consists of a nonpolarizing 50:50 beamsplitter forming two arms. This set up is placed at one of the output ports of a confocal fluorescence microscope. The time interval \( \tau \) between two consecutively detected photons in separate arms is measured by a 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. 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 7 shows some results of freshmen group of their 12-hour research project (course “Optics in information age”): left – time traces of count rate on one of APD detectors showing “blinking” of CdSeTe colloidal quantum dots, right – fluorescence antibunching curve (CdSeTe quantum dot) with a dip at zero interphoton time (from freshmen group presentation).
Figure 7. Some freshmen group results: left – time traces of photon count showing “blinking” of CdSeTe colloidal quantum dots; right – fluorescence antibunching curve (CdSeTe colloidal quantum dot).

**Single Photon Source III: Mobile source of single photons based on color centers in nanodiamonds**

During this first year of the project we accomplished the main work on preparation of a mobile SPS with excitation of a stable, unbleachable single emitter (single color center in nanodiamond) through the optical fiber. This SPS can be easily transported to other Universities.

Both freshmen of 12-hour research project and students enrolled with 4-credit hour course were able to obtain imaging and fluorescence antibunching from single color centers in nanodiamonds. Figure 8, left shows image of single NV-color center fluorescence using confocal fluorescence microscope. Figure 8, right shows histogram-indicated fluorescence antibunching of this single emitter.

Figure 8. Preparation of a compact transportable SPS based on color centers in nanodiamonds in cholesteric liquid crystal chiral photonic bandgap host: Left and center – freshmen research results (Confocal microscope fluorescence image of color centers and histogram of coincidence counts from color center showing dip at zero interphoton time (fluorescence antibunching). Right figure shows color center fluorescence antibunching in cholesteric host of Lukishova’s research group.
2. PROVIDED OPPORTUNITIES FOR TRAINING AND DEVELOPMENT

More than 100 students benefited from the project during the first year of funding. The groups of trained students with different level are listed below:

(1) **10 students** (two groups) of freshmen OPT 101 course “Optics in the Information Age” (Knox) carried out 12 hour research projects on single photon source and single photon interference (Lukishova).

(2) **25 students** (four groups) of freshmen OPT 101 course “Optics in the Information Age” (Knox) participated in lecture-demonstrations of four teaching experiments in quantum optics (Lukishova). This demonstration provided students a laboratory experience with the concepts that they studied on the lectures (e.g., single-photon interference, entanglement, fluorescence, etc.)

(3) **17 students** (four groups) of OPT 223 course “Quantum mechanics of Optical Materials and Devices” (Stroud), carried out two 3-hour labs (entanglement and Bell’s inequality and single photon interference using Young double slit and Mach-Zehnder interferometer).

(4) **14 students** of Monroe Community College of Modern Physics course (D’Alessandris) carried out two three hour labs (D’Alessandris, Lukishova) at the University of Rochester (entanglement and Bell’s inequality and single photon interference using Young double slit and Mach-Zehnder interferometer).

(5) **7 students** of four-credit hour course OPT253 “Quantum Optics and Quantum Information Laboratory” A
teaching assistant of this course was also trained.

(6) **35 students** (3 groups) and their teachers from Brighton high school participated in lecture-demonstrations of quantum optics laboratory (Knox, Lukishova).

In addition, three graduate and one undergraduate student carried out research projects using different modules of this teaching laboratory facility.

### 3. OUTREACH ACTIVITIES

1. See (6) of Section 2 (Lecture-demonstrations of quantum optics laboratory to Brighton high-school students and teachers (Knox, Lukishova);


3. Lukishova is invited this September to the University of Oklahoma (Tulsa) to give a talk as well as to discuss challenges in organizing quantum optics laboratory.

### 4. EVALUATION OF STUDENTS’ KNOWLEDGE AND LABORATORY COURSE SUCCESS

To monitor students’ activity in the classroom as well as to evaluate students’ knowledge and course success, we used both formative and summative evaluation techniques which tell us (1) whether students like these labs and what needs to be improved; (2) whether students mastered particular concepts.

We evaluated four groups of students: (1) UR students who took 15-hour version of the OPT 253 labs (5 from total 7 students participated in this evaluation); (2) UR students who took three-hour lab versions (OPT 223) (14 students from total 17 participated in this evaluation); (3) Monroe Community College students (three-hour versions of the labs) (13 and 14 students from total 14 students participated in this evaluation); (4) UR freshmen of OPT 101 course 12-hour research projects (10 students from total 25 students participated in this evaluation).

**Formative evaluation** was carried out by 5 students enrolled in the laboratory course taught by Lukishova (OPT 253). These evaluations took place both in oral (after each lab) and in written (after the whole course) forms. All students evaluated the course very positive indicating the success of the course. At the end of “Project Activities and Findings” section we attached written students’ opinion about this course which was sent us by the Dean’s office).
Summative evaluation was accomplished by two ways: (1) using different questionnaires (without grading) and (2) using the grades for each lab. Teaching assistants helped in summative evaluation. Histogram in Figure 14 shows percent of correct answers to seven questions of Lab 1 for OPT 223 students after lab completion.

![Figure 14. Histogram of evaluation of student learning for OPT 223 labs.](image)

Figure 14. Histogram of evaluation of student learning for OPT 223 labs.

Figure 15 shows the same histograms (Labs 1 and 2) for Monroe Community College students. Two laboratory activities (single photon interference and entanglement) from the Quantum Optics and Quantum Information Laboratory course at the University of Rochester (OPT 253) were adapted into a three-hour format appropriate for sophomore level Modern Physics students at Monroe Community College (PHY 262). 14 students enrolled in Modern Physics at MCC conducted these experiments at UR in groups of 4 or 5. MCC students participated in a brief tutorial on the theoretical issues involved in the experiments before visiting UR and completed a conceptual evaluation at the conclusion of each experiment. Students are also informally debriefed on the experience upon their return to MCC.

Figure 15. Histograms of evaluation of student learning for Monroe Community College students.

Figure 16 shows the result of evaluation of learning for freshmen of OPT101.

![Figure 16. Histogram of evaluation of freshmen learning (OPT 101 course research projects).](image)

Figure 16. Histogram of evaluation of freshmen learning (OPT 101 course research projects).

Questionnaire with 32 questions on photon quantum mechanics of OPT 253 course showed that percent of correct answers of all students was greater than 90%. Table 1 shows each student performance.
Students’ mastery in photon-counting instrumentation of OPT 253 course showed that 60% of students received total scores of “A” and the rest of students received total scores of “A-“. (Students were permitted to rewrite their reports). The grades were based on students’ capability of carrying out the experiments, writing the reports, delivering oral presentations and answering questions during Mid Term and Final Exams.

5. PUBLICATIONS AND PRESENTATIONS (first year of the project)

5.1. Journal publications and periodically published conference proceedings


5.2. One-time publications in conference proceedings


5.3. Website:

http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/
<table>
<thead>
<tr>
<th>Instructor</th>
<th>Avg eval score</th>
<th>Text Responses</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>&gt; 75%</td>
<td>The concepts in this course were difficult to understand. A lot of research was done during my lab report write ups.</td>
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<tr>
<td></td>
<td>&gt; 75%</td>
<td>I worked hard with this course. Before the lab, I read the manual. In the experiment, I carefully recorded each steps, and discussed with the Professor and classmates, and quite involved in the lab. After the lab, I took the lab report carefully.</td>
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<tr>
<td></td>
<td>&gt; 75%</td>
<td>I walked into the course with no knowledge of Quantum Optics whatsoever. Now that this is I have no previous knowledge of quantum mechanics, I learned a lot from this course, and I believe it will help me next semester when I take quantum optics.</td>
</tr>
<tr>
<td></td>
<td>&gt; 75%</td>
<td>Quantum Optics is new area for me. I learned the theory of Quantum Mechanics before. While, this Quantum Optics Lab gives me direct experiences of quantum. We can make quantum photons with our own hands, and can observe their quantum characters. We also work with some advanced instruments.</td>
</tr>
<tr>
<td></td>
<td>&gt; 75%</td>
<td>Doctor was able to tell us clearly what the point of everything we were doing was, whether it be in the manual, syllabus or discussions.</td>
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<tr>
<td></td>
<td>&gt; 75%</td>
<td>N/A</td>
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<tr>
<td></td>
<td>&gt; 75%</td>
<td>Very good.</td>
</tr>
<tr>
<td></td>
<td>&gt; 75%</td>
<td>To know and understand the lab manuals was imperative to understanding what had to be done during each lab session and a proper right-up!</td>
</tr>
<tr>
<td></td>
<td>&gt; 75%</td>
<td>The readings provided in the course, like the lab manual was crucial to performing well in the lab.</td>
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<tr>
<td></td>
<td>&gt; 75%</td>
<td>In this course, the most important is taking part in the experiment. And for me, the second important is reading. To understand the thoery, and to know how to do the experiment, I need to read papers and manuals. It is very important and I learned a lots in reading.</td>
</tr>
<tr>
<td></td>
<td>&gt; 75%</td>
<td>Any extra reading pertained exactly to what we were trying to accomplish in the labs. And they were very informative and interesting!</td>
</tr>
<tr>
<td></td>
<td>&gt; 75%</td>
<td>There were lab reports, an essay, a presentation, a midterm, and a final. They all supported the course objectives.</td>
</tr>
<tr>
<td></td>
<td>&gt; 75%</td>
<td>The assignments and exams are mostly about the experiment process and theory. So as long as you take part in the experiments and understand every steps and results, the assignments and exams are not very difficult.</td>
</tr>
<tr>
<td></td>
<td>&gt; 75%</td>
<td>Starting from scratch and working all the way up to a full understanding is exactly what any class should do. This was by far the best class that has ever actually been just that: a class - a learning experience to gain knowledge and better ones education and understanding. This may have even benefited more since it was a lab course. I feel like I learned more &quot;material&quot; working in the lab every day than I have in lectures and homeworks with other classes. I can’t write enough of a glowing review.</td>
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<tr>
<td></td>
<td>&gt; 75%</td>
<td>Very beneficial course. Working with a very smart instructor who knows her quantum. Worked with equipment that many people have the chance to work with.</td>
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<tr>
<td></td>
<td>&gt; 75%</td>
<td>I think it worths the time and efforts.</td>
</tr>
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</table>

Question: **What are the major strengths of this course?**
<table>
<thead>
<tr>
<th>Question: What are the major weaknesses of this course? Please make suggestions for improvement.</th>
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<tbody>
<tr>
<td>&gt; 75% I feel like it needs to get bigger! While the small group was fantastic, I wish that more people would become involved so that it gains the momentum and attention it deserves!</td>
</tr>
<tr>
<td>&gt; 75% Big groups is definitely a negative in the lab. I understand the professor had to be with us in the lab most of the time because of the research equipment, but without here presence, the TA made a very good job ensuring the students’ and equipments’ safety. Smaller groups would definitely help, more hands on time for each person. There 5 students in this course and we all did the same presentation, with the same experimental data. In the future, I believe it could be more beneficial if each student focuses on one lab, or make the presentations in Groups. Lastly, Assign the essay earlier in the semester. Last week of the semester just for this class, there was a final, presentation, essay, and lab 3 and 4 due.</td>
</tr>
<tr>
<td>Question: Comments:</td>
</tr>
<tr>
<td>LUKISHOVA &gt; 75% There was never a time when she was unable to answer a question or approach it in a way that would make sense. Her labs were built so that we learned as we went, and when we fully understood how to handle the experiment, we were able to do it practically all by ourselves. In other words: we were taught, we learned it, and we excelled. Doctor Lukishova had an extreme impact on that happening.</td>
</tr>
<tr>
<td>LUKISHOVA &gt; 75% Professor Lukishova took part in all the experiments with students. First, she would ask how much do we know about the exam, and then she show us how to do, and let us do it ourselves one by one. Every students are encourged to do the experiments and ask questiones. Besides the manual, she also gave lectures, which cover wider information about the lab which are very helpful.</td>
</tr>
<tr>
<td>Question: Comments:</td>
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<tr>
<td>LUKISHOVA &gt; 75% I had a very vague understanding of what all the topics we touched on were, and even less of how it could be at all practical. Now, I can speak better on each of them then any of my colleagues. Not to mention, I have always had an interest in what the next &quot;big thing&quot; has been, and this whole course is based on what IS going to be the future of practically all technology. It was very eye-opening and exciting to work on such material. I hope I get to do it again in the future.</td>
</tr>
<tr>
<td>LUKISHOVA &gt; 75% She made it look easy.</td>
</tr>
<tr>
<td>LUKISHOVA &gt; 75% It is very free in this class. Whenever you have questions, we can discuss with the Professor. And no intense pressure about assignments and exam, because we usually have enough time, and we can improve them. So it makes me more relax to do it, and be willing to pay more efforts to get a higher score.</td>
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<td>Question: Comments:</td>
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<td>LUKISHOVA &gt; 75% Thanks again. Not only was it fun and entertaining most of the time, but the experience I have gained really excites me. I truly believe I have finally learned something from taking a course.</td>
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<tr>
<td>LUKISHOVA &gt; 75% I greatly recommend this course for students who are interested in quantum and quantum optics.</td>
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<tr>
<td>Question: Comments:</td>
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<tr>
<td>LUKISHOVA &gt; 75% She says it best: we are students, we are learning, don’t be afraid to get anything wrong, you must try and learn. I wish every professor / teacher / mentor, whatEVER had this mentality towards passing knowledge on. It was incredibly easy to learn everything from Doctor Lukishova because she understood that we were, well, just students and just gaining the abilities to discern what is actually going on. She cared an almost ridiculous amount about how well we took on the material. It was awesome to have a teacher really be there every step of the way and make sure that we got every inch of material.</td>
</tr>
<tr>
<td>LUKISHOVA &gt; 75% Meetings were easy to set, and will meet with you whenever you need. She is a very caring instructor, she insures that everyone understands the material before moving on.</td>
</tr>
<tr>
<td>LUKISHOVA &gt; 75% My classmates and I always discussed with Professor Lukishova. She often inspired students to ask questions.</td>
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<tr>
<td>Question: What are the major strengths of this instructor?</td>
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<tr>
<td>LUKISHOVA &gt; 75% Working with cutting edge material, doing true research as an undergraduate, learning lab protocol. I believe that my write-ups for future anything will be greatly improved after having gone through this course.</td>
</tr>
<tr>
<td>LUKISHOVA &gt; 75% State of the art equipment, caring and very knowledgeable professor.</td>
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<td>LUKISHOVA &gt; 75% It gives us the first-hand experiences of quantum optics.</td>
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<td>LUKISHOVA</td>
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<td>LUKISHOVA</td>
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**Question: What are the major weaknesses of this instructor? Please make suggestions for improvement.**

| LUKISHOVA | > 75% | To cite a weakness would be a flaw in itself. I had NO problems all semester and find it hard to even fathom that someone would have a problem with how she conducted everything. |
| LUKISHOVA | > 75% | organization, especially with due dates. |

**Question: If there are any other further comments you would like to make about this course, please do so in the space provided below.**

<p>| LUKISHOVA | &gt; 75% | I am going to parade the need for this course to be taken around to everyone. Every underclassmen I know better be signed up. I would be very upset if this course went unnoticed for any longer! |</p>
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<th>Question Text</th>
<th>N</th>
<th>Top Two</th>
<th>Avg</th>
<th>Major</th>
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<td>Student increase knowledge</td>
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<td>Rate yourself in course</td>
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<td>0%</td>
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<td>Syllabus describe course content</td>
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<td>4.8</td>
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<td>Readings were important in my learning of the course</td>
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<td>100%</td>
<td>5</td>
<td>100%</td>
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<td>100%</td>
<td>0%</td>
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<tr>
<td>Did assignments and exams support objectives</td>
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<td>100%</td>
<td>4.8</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>Excellent</td>
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<tr>
<td>Responsiveness (LUKISHOVA)</td>
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<td>5</td>
<td>100%</td>
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<td>Effectiveness (LUKISHOVA)</td>
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<td>Str Agree</td>
<td>100%</td>
<td>0%</td>
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<tr>
<td>Have a stronger interest in this subject because of this instructor (LUKISHOVA)</td>
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<td>100%</td>
<td>4.8</td>
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<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>Excellent</td>
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<td>Poor</td>
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Project Activities and Findings

First Year (June 09 – May 10) Award No: 0920500

Collaborative Research – CCLI Phase II: Diverse Partnership for Teaching Quantum Mechanics and Modern Physics with Photon Counting Instrumentation

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Goals and Objectives (4-year project)
The central task of this project 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. The project will impact the curricula of three Departments of the University of Rochester (UR), two community colleges (Monroe and Corning), liberal art college for women, Bryn Mawr; Rochester Institute of Technology, Adelphi University, and two other colleges that will be identified after a 4th year workshop. The project goals are as follows:

1. Improvement of student learning at these diverse educational institutions in quantum mechanics and modern physics. The basis for achieving this goal is the experience of the UR (Phase I project) and educational practices from the STEM educational knowledge base on photon quantum mechanics teaching laboratories;

2. Providing photon-counting instrumentation skills to the future workforce;

3. Increasing feedback between teaching and learning by involving undergraduate students in planning and decisions during building the teaching laboratory;

4. Involvement of undergraduate students in the research process by using research setups and samples in the undergraduate teaching laboratory;

5. Effective dissemination of project results to the broader education community and contribution to the STEM educational knowledge base.

During the first year period of funding three institutions worked on the initial tasks of the project: University of Rochester, Rochester Institute of Technology and Monroe Community College. Our main research and education activities have been focused on the following challenges:

- Developing “mini-labs” (three-hour versions for teaching experiments built during the Phase I project): (1) entanglement lab; (2) single-photon interference lab; single photon source labs: (3) single emitter confocal fluorescence microscopy; (4) fluorescence antibunching, and Hanbury Brown-Twiss interferometer.

- Developing independent program of quantum optics teaching experiments at the Rochester Institute of Technology (RIT) using the experience gained at the UR. Prof. Jodoin, co-PI of the project, spent his Fall 2009 sabbatical at the UR working with Dr. Lukishova on one of the versions of the entanglement lab which can be implemented at RIT, as well as on single...
photon interference lab. Under the mentoring of Lukishova Jodoin performed existing experiments on single photon interference and a test of Bell’s inequality using quantum entanglement. With this background and experience he worked on a new setup to do quantum entanglement using a blue diode laser as the source for parametric down-conversion. This involved aligning the optics and assembling and testing a new coincidence counter that interfaced to a computer using LabView.

- As an additional educational experience for RIT, Jodoin audited Stroud’s course on quantum optics and attended several colloquia hosted by the Institute of Optics.

- Jodoin is currently developing the laboratory portion of a new quantum optics course at RIT. His colleague in the Physics Department, Edwin Hach, is designing the lecture part of the course. They are collaborating with Stefan Preble in the Microsystems Engineering Program, who is supplying some of the needed equipment. For the RIT laboratories Jodoin has designed four experiments based on those that he did at the Institute of Optics (UR). They are (1) single photon interference, (2) the quantum eraser, (3) characterization of parametric down-conversion, and (4) a test of Bell’s inequality. The equipment is currently in house or being purchased so that the course can be offered next academic year.

- To prepare typical physics undergraduates at RIT for the experiments, Jodoin has written a comprehensive set of pre-laboratory notes. These include the history and significance of the experiments and mathematical derivations of the results expected from quantum theory.

- Developing lecture materials on entanglement and Bell’s inequalities to facilitate students’ understanding of labs [Lukishova, Jodoin, Stroud in collaboration with Eberly (Department of Physics, UR)];

- Developing and teaching 4-credit-hour course on Quantum Optics and Quantum Information Laboratory (Lukishova) to seven students from three departments;

- Preparation and teaching of two “mini-labs” labs at the UR facilities to 3 groups of 14 students of Monroe Community College (MCC). Entanglement lab was taught by Lukishova (UR), single photon interference lab – by D’Alessandris (MCC).

- Preparation and teaching two “mini-labs” to 4 groups of 17 seniors of the UR lecture course “Quantum mechanics of optical materials and devices” (Stroud). Entanglement lab was taught by Lukishova, single photon interference lab – by a TA.

- 12-hour freshmen research projects of “Optics in the Information Age” course (2 groups of 10 students) on room-temperature single photon source and single photon interference (Lukishova, Knox);

- Students’ research on room-temperature polarized single photon source (Lukishova)

- Lecture-demonstrations of four quantum optics experiments to 25 students of the course “Optics in the Information Age” (Lukishova, Knox);

- Lecture-demonstrations of quantum optics experiments to 3 groups of 35 high-school students and their teachers;

- Sharing the new equipment with other research groups, for instance, (i) single-photon EM-CCD-camera, Newport picometer has been used in students’ research of Boyd’s group on
quantum optics. Boyd’s students carried out a research project using the confocal microscope setup with antibunching measurements (Labs 3-4). Novotny’s students used the entanglement setup and EM-CCD-camera for their research project.

- Evaluation of students’ knowledge by questionnaires, report and essay writing, and oral presentations. Evaluation of the first step of the project by the internal evaluator;
- Dissemination of results by writing papers and conference paper submission;
- Website preparation of the course “Quantum Optics and Quantum Information Laboratory (http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab). Linking this website with NSF supported the Quantum Exchange and ComPadre sites.
- Dissemination of results by demonstration of teaching experiments to Prof. E. Galvez (Colgate University), professors Capasso (Harvard University), Aspect (Institute D’Optique, France), Belyakov (Landau Institute for Theoretical Physics, Russia), and other visitors of the Institute of Optics (UR);
- In addition to current rooms for teaching labs (210 sq. feet, 175.4 sq. feet and 242 sq. feet), the Institute of Optics provided an office room (175.4 sq. feet) which was used by visitors and collaborators.
- Outreach activities (see details below).

More details of our activities with the main results and findings are described below. Here are the highlights of these findings:

Contribution to knowledge base outcome:
- Four teaching experiments in quantum mechanics and modern physics are in development by UR, RIT and MCC for students of diverse educational institutions. (Lukishova, Stroud, Jodoin, D’Alessandris, graduate student Bissell, undergraduate students):
  - entanglement and Bell’s inequalities;
  - single-photon source interference in Young’s double-slit and Mach-Zehnder interferometers;
  - confocal fluorescence microscopy of single-emitter fluorescence;
  - Hanbury Brown and Twiss setup and fluorescence antibunching.
- Manuals were written for four experiments with photon counting instrumentation.
- Lecture materials on entanglement and Bell’s inequalities for facilitation of student’s understanding were prepared after intensive discussions with leading quantum optics scientists and teachers.
- Students participated in this project co-authored one published paper, two accepted papers, three accepted conference summaries.

Learning outcome:
- During this first year of the project more than 100 students benefited from these teaching experiments. Among them are students of three departments of the UR, including 25 freshmen, MCC, RIT as well as students and teachers from Brighton High School.
Using questionnaires on photon quantum mechanics showed that 63% of OPT 223 students (UR) answered correctly 90% of questions, 60% of MCC students answered correctly 80% of questions and 60% of freshmen of OPT 101 (UR) participating in research answered correctly 70% of questions.

Students’ mastery in photon-counting instrumentation of 4-credit hour course with 15-hour labs is shown in that 60% of students received total scores of “A” and the rest of students received total scores of “A-“. The grades were based on students’ capability of carrying out the experiments, writing the reports and delivering oral presentations. All students answered correctly 90% of questions.

Community building outcome:
- Three Rochester educational institutions (UR, MCC, RIT) collaborate and share their experience on improvement of student learning at these diverse educational institutions in quantum mechanics and modern physics.
- We interacted with investigators of other universities and counties working on similar or related approaches: Galvez (Colgate University), Beck (Whitman College), Bentley (Adelphi University), Noel (Bryn Mawr College).
- Teaching experiments were shown to Capasso (Harvard University), Aspect (Institute d’Optique, France), Belyakov (Landau Institute for Theoretical Physics (Russia), and other visitors of the Institute of Optics.
- Our website of Quantum Optics and Quantum Information Laboratory has already more than 1,700 visitors. Some people contact us directly by e-mails.
- Prof. Stroud delivered invited lecture in Pennsylvania, Lukishova was invited to deliver her lecture in Oklahoma this September.

Below is a more detailed description of some above-mentioned findings. This first year of the project was devoted to developing of quantum optics teaching experiments at RIT using the experience of UR, developing and teaching 3 hour versions of four teaching labs (“mini-labs”) for UR and MCC, preparing lecture materials for the labs, teaching the 4-credit hour course, lecture-demonstrations to students of different experience including freshmen and high-school students, work on a mobile single-photon source device, starting data collection for evaluation of students’ knowledge and the first evaluation of the project by the internal evaluator.

1. DESCRIPTION OF TEACHING EXPERIMENTS WITH EXPERIMENTAL RESULTS PERFORMED BY STUDENTS OF DIFFERENT LEVELS

Lab. 1. Entanglement and Bell’s inequalities
The schematic of the teaching experiment on polarization-entangled photons and Bell’s inequalities is shown in the Figure 1, left. We used P. Kwiat approach [Phys. Rev A. 60, R773 (1999)]. Light from the laser passes through a pair of type I BBO crystals that are mounted back-to-back with one rotated 90° 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 A and B). These two APDs are located on two diametrically opposite points of the down-converted cone. In this arrangement each crystal can support downconversion of one pump polarization (H or V). A 45° polarized pump photon can be downconverted in either crystal, producing a polarization entangled pair of photons:
\[|H\rangle + |V\rangle \rightarrow |V', V\rangle + \exp(i\Delta)|H, H\rangle.\] Quartz plate rotation compensates phase \(\Delta\) introduced by the crystals. Coincidences are detected by a fast logic circuit (counter) card inside a PC. Figure 1, right (obtained by the students of 3-hour-lab version) 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 \(\alpha\) of the linear polarizer A varies at two different fixed angles \(\beta\) of the polarizer B. Calculation of Bell’s inequality in the Clauser-Horn-Shimony-Holt form shows its violation (\(S > 2\)).

![Fig. 1](image1.png)

Figure 1. Entanglement and Bell’s inequalities lab: left – schematics of the experiment (interference filters transmitted only downconverted light 727.6 nm are placed in front of each detector); right – coincidence count dependence on relative polarizer angle in front of detectors A and B. High fringe visibility (greater than 0.71) indicates Bell’s inequality violation and entanglement.

UR has two experimental setups located in different rooms with different lasers and different BBO crystal sets. One setup (Figure 2) was used for teaching experiments, another (Figure 3) – for modeling of the RIT version of this lab. For UR teaching labs we use an 100 mW, 363.8 nm, cw argon ion laser donated by Spectra Physics division of Newport Corporation. The results on this setup are very reproducible and we used it for quick demonstration of photon entanglement during only 2-3 hours of “mini-lab” for several groups of students of different levels (UR and MCC).

![Fig. 2](image2.png)

Figure 2. Entanglement lab setup with an argon ion laser (left) and its entangled photon registration module (right).

This setup also permits students to observe and prepare video files of the cone of downconverted photons using a low-light level EM-CCD camera.

The second setup with 10 mW, 406 nm excitation (diode laser) is shown in Figure 3. This setup was described in papers of D. Dehlinger and M.W. Mitchell [Am. J. Phys., 70, 898 and 903 (2002)]. Jodoin (RIT) during his sabbatical at the UR and Lukishova worked on developing
an easier method of alignment of this setup as well as on the use of a cheap computer board for coincidence count measurements.

Figure 3. Part of entanglement lab setup with a diode laser excitation (left) (APDs and polarizers are not shown) and its entangled photon registration module with APDs and polarizers (right).

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 are made using a He-Ne laser beam, attenuated to the single photon level and an EM-CCD camera (Figure 4, left). Mach-Zehnder interferometer (Figure 4, right) is used for the demonstration of a single-photon interference after removing “which-way” information (identification of the path). Figure 5 shows photographs of experimental setup (left) and one of three groups of Monroe Community College students carrying out this experiment.

Figure 4. Left: Single-photon interference using Young’s double-slit at different exposure time. Right: Mach-Zehnder interferometer schematics for “which-way experiment

Figure 5. Photograph of single-photon interference setup with low-light level EM-CCD-camera (left); group of MCC students (right) carrying out this experiment.
Lab 3. Single photon source I: Confocal microscope imaging of single-emitter fluorescence

This Lab and the next, Lab 4, are devoted to a single-photon source (SPS) with photons separated in time (antibunching). To produce single photons, excited laser beam should be focused on a single emitter which produces single photon at a time. SPS is the key hardware element of quantum cryptography. At the same time methods and instrumentation of confocal fluorescence microscopy are widely used in nanotechnology, biology and biomedicine.

Laser excitation at 532-nm (8 ps pulse duration, 76 MHz pulse repetition rate) as well as at 514 nm (cw) was used for confocal microscope single-emitter fluorescence imaging in the teaching labs (Figure 6). Colloidal semiconductor quantum dots and single color-centers in nanodiamonds were used as single emitters.

Students enrolled in the laboratory course also participated in research. They carried out imaging of single emitter fluorescence in photonic bandgap cholesteric liquid crystal hosts and photon antibunching measurements, observed “blinking” of quantum dots using raster scan or wide-field microscopy with EM-CCD camera.

Figure 6. Left: Photograph of a confocal fluorescence microscope for SPS applications; Right: Freshmen work on 12-hour research project of “Optics for information age” course (Fall 2009).

Lab. 4. Single Photon Source II: Hanbury Brown and Twiss setup. Fluorescence antibunching

Hanbury Brown and Twiss interferometer for fluorescence antibunching measurements consists of a nonpolarizing 50:50 beamsplitter forming two arms. This set up is placed at one of the output ports of a confocal fluorescence microscope. The time interval \( \tau \) between two consecutively detected photons in separate arms is measured by a 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. 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 7 shows some results of freshmen group of their 12-hour research project (course “Optics in information age”): left – time traces of count rate on one of APD detectors showing “blinking” of CdSeTe colloidal quantum dots, right – fluorescence antibunching curve (CdSeTe quantum dot) with a dip at zero interphoton time (from freshmen group presentation).
Figure 7. Some freshmen group results: left – time traces of photon count showing “blinking” of CdSeTe colloidal quantum dots; right – fluorescence antibunching curve (CdSeTe colloidal quantum dot).

**Single Photon Source III: Mobile source of single photons based on color centers in nanodiamonds**

During this first year of the project we accomplished the main work on preparation of a mobile SPS with excitation of a stable, unbleachable single emitter (single color center in nanodiamond) through the optical fiber. This SPS can be easy transported to other Universities.

Both freshmen of 12-hour research project and students enrolled with 4-credit hour course were able to obtain imaging and fluorescence antibunching from single color centers in nanodiamonds. Figure 8, left shows image of single NV-color center fluorescence using confocal fluorescence microscope. Figure 8, right shows histogram-indicated fluorescence antibunching of this single emitter.

Figure 8. Preparation of a compact transportable SPS based on color centers in nanodiamonds in cholesteric liquid crystal chiral photonic bandgap host: Left and center – Freshmen research results (Confocal microscope fluorescence image of color centers and histogram of coincidence counts from color center showing dip at zero interphoton time (fluorescence antibunching). Right figure shows color center fluorescence antibunching in cholesteric host of Lukishova’s research group.
2. PROVIDED OPPORTUNITIES FOR TRAINING AND DEVELOPMENT

More than 100 students benefited from the project during the first year of funding. The groups of trained students with different level are listed below:

(1) 10 students (two groups) of freshmen OPT 101 course “Optics in the Information Age” (Knox) carried out 12 hour research projects on single photon source and single photon interference (Lukishova).

(2) 25 students (four groups) of freshmen OPT 101 course “Optics in the Information Age” (Knox) participated in lecture-demonstrations of four teaching experiments in quantum optics (Lukishova). This demonstration provided students a laboratory experience with the concepts that they studied on the lectures (e.g., single-photon interference, entanglement, fluorescence, etc.)

(3) 17 students (four groups) of OPT 223 course “Quantum mechanics of Optical Materials and Devices” (Stroud), carried out two 3-hour labs (entanglement and Bell’s inequality and single photon interference using Young double slit and Mach-Zehnder interferometer).

(4) 14 students of Monroe Community College of Modern Physics course (D’Alessandris) carried out two three hour labs (D’Alessandris, Lukishova) at the University of Rochester (entanglement and Bell’s inequality and single photon interference using Young double slit and Mach-Zehnder interferometer).

(5) 7 students of four-credit hour course OPT253 “Quantum Optics and Quantum Information Laboratory” A
teaching assistant of this course was also trained.

(6) **35 students** (3 groups) and their teachers from Brighton high school participated in lecture-demonstrations of quantum optics laboratory (Knox, Lukishova).

In addition, three graduate and one undergraduate student carried out research projects using different modules of this teaching laboratory facility.

3. **OUTREACH ACTIVITIES**

1. See (6) of Section 2 (Lecture-demonstrations of quantum optics laboratory to Brighton high-school students and teachers (Knox, Lukishova);


3. Lukishova is invited this September to the University of Oklahoma (Tulsa) to give a talk as well as to discuss challenges in organizing quantum optics laboratory.

4. **EVALUATION OF STUDENTS’ KNOWLEDGE AND LABORATORY COURSE SUCCESS**

To monitor students’ activity in the classroom as well as to evaluate students’ knowledge and course success, we used both formative and summative evaluation techniques which tell us (1) whether students like these labs and what needs to be improved; (2) whether students mastered particular concepts.

We evaluated four groups of students: (1) UR students who took 15-hour version of the OPT 253 labs (5 from total 7 students participated in this evaluation); (2) UR students who took three-hour lab versions (OPT 223) (14 students from total 17 participated in this evaluation); (3) Monroe Community College students (three-hour versions of the labs) (13 and 14 students from total 14 students participated in this evaluation); (4) UR freshmen of OPT 101 course 12-hour research projects (10 students from total 25 students participated in this evaluation).

*Formative evaluation* was carried out by 5 students enrolled in the laboratory course taught by Lukishova (OPT 253). These evaluations took place both in oral (after each lab) and in written (after the whole course) forms. All students evaluated the course very positive indicating the success of the course. At the end of “Project Activities and Findings” section we attached written students’ opinion about this course which was sent us by the Dean’s office).
**Summative evaluation** was accomplished by two ways: (1) using different questionnaires (without grading) and (2) using the grades for each lab. Teaching assistants helped in summative evaluation. Histogram in Figure 14 shows percent of correct answers to seven questions of Lab 1 for OPT 223 students after lab completion.

![Figure 14. Histogram of evaluation of student learning for OPT 223 labs.](image1.png)

Figure 14. Histogram of evaluation of student learning for OPT 223 labs.

![Figure 15. Histograms of evaluation of student learning for Monroe Community College students.](image2.png)

Figure 15. Histograms of evaluation of student learning for Monroe Community College students.

Figure 15 shows the same histograms (Labs 1 and 2) for Monroe Community College students. Two laboratory activities (single photon interference and entanglement) from the Quantum Optics and Quantum Information Laboratory course at the University of Rochester (OPT 253) were adapted into a three-hour format appropriate for sophomore level Modern Physics students at Monroe Community College (PHY 262). 14 students enrolled in Modern Physics at MCC conducted these experiments at UR in groups of 4 or 5. MCC students participated in a brief tutorial on the theoretical issues involved in the experiments before visiting UR and completed a conceptual evaluation at the conclusion of each experiment. Students are also informally debriefed on the experience upon their return to MCC.

Figure 16 shows the result of evaluation of learning for freshmen of OPT101.

![Figure 16. Histogram of evaluation of freshmen learning (OPT 101 course research projects).](image3.png)

Figure 16. Histogram of evaluation of freshmen learning (OPT 101 course research projects).

Questionnaire with 32 questions on photon quantum mechanics of OPT 253 course showed that percent of correct answers of all students was greater than 90%. Table 1 shows each student performance.
Table 1. Percent of correct answers of each of 5 students participated in evaluation of their knowledge for OPT 253 course Quantum Optics and Quantum Information laboratory (Lukishova).

Students’ mastery in photon-counting instrumentation of OPT 253 course showed that 60% of students received total scores of “A” and the rest of students received total scores of “A-“. (Students were permitted to rewrite their reports). The grades were based on students’ capability of carrying out the experiments, writing the reports, delivering oral presentations and answering questions during Mid Term and Final Exams.

5. PUBLICATIONS AND PRESENTATIONS (first year of the project)

5.1. Journal publications and periodically published conference proceedings


5.2. One-time publications in conference proceedings


5.3. Website:

http://www.optics.rochester.edu/workgroups/lukishova/QuantumOpticsLab/
<table>
<thead>
<tr>
<th>Instructor</th>
<th>Avg eval score</th>
<th>Text Responses</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td><strong>Question: Comments:</strong></td>
</tr>
<tr>
<td>&gt; 75%</td>
<td>The concepts in this course were difficult to understand. A lot of research was done during my lab report write ups.</td>
<td></td>
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<tr>
<td>&gt; 75%</td>
<td>I worked hard with this course. Before the lab, I read the manual. In the experiment, I carefully recorded each steps, and discussed with the Professor and classmates, and quite involved in the lab. After the lab, I took the lab report carefully.</td>
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<tr>
<td>&gt; 75%</td>
<td>I walked into the course with no knowledge of Quantum Optics whatsoever. Now that this is I have no previous knowledge of quantum mechanics, I learned a lot from this course, and I believe it will help me next semester when I take quantum optics.</td>
<td></td>
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<tr>
<td>&gt; 75%</td>
<td>Quantum Optics is new area for me. I learned the theory of Quantum Mechanics before. While, this Quantum Optics Lab gives me direct experiences of quantum. We can make quantum photons with our own hands, and can observe their quantum characters. We also work with some advanced instruments.</td>
<td></td>
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<tr>
<td>&gt; 75%</td>
<td>Doctor was able to tell us clearly what the point of everything we were doing was, whether it be in the manual, syllabus or discussions.</td>
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<tr>
<td>&gt; 75%</td>
<td>N/A</td>
<td></td>
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<tr>
<td>&gt; 75%</td>
<td>Very good.</td>
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<tr>
<td>&gt; 75%</td>
<td>To know and understand the lab manuals was imperative to understanding what had to be done during each lab session and a proper right-up!</td>
<td></td>
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<tr>
<td>&gt; 75%</td>
<td>The readings provided in the course, like the lab manual was crucial to performing well in the lab.</td>
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<tr>
<td>&gt; 75%</td>
<td>In this course, the most important is taking part in the experiment. And for me, the second important is reading. To understand the thoery, and to know how to do the experiment, I need to read papers and manuals. It is very important and I learned a lots in reading.</td>
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<tr>
<td>&gt; 75%</td>
<td>Any extra reading pertained exactly to what we were trying to accomplish in the labs. And they were very informative and interesting!</td>
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<tr>
<td>&gt; 75%</td>
<td>There were lab reports, an essay, a presentation, a midterm, and a final. They all supported the course objectives.</td>
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<tr>
<td>&gt; 75%</td>
<td>The assignments and exams are mostly about the experiment process and theory. So as long as you take part in the experiments and understand every steps and results, the assigment and exams are not very difficult.</td>
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<tr>
<td>&gt; 75%</td>
<td>Starting from scratch and working all the way up to a full understanding is exactly what any class should do. This was by far the best class that has ever actually been just that: a class - a learning experience to gain knowledge and better ones education and understanding. This may have even benefited more since it was a lab course. I feel like I learned more &quot;material&quot; working in the lab every day than I have in lectures and homeworks with other classes. I can’t write enough of a glowing review.</td>
<td></td>
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<tr>
<td>&gt; 75%</td>
<td>Very beneficial course. Working with a very smart instructor who knows her quantum. Worked with equipment that many people have the chance to work with.</td>
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<tr>
<td>&gt; 75%</td>
<td>I think it worths the time and efforts.</td>
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**Question: What are the major strengths of this course?**
> 75% Working with cutting edge material, doing true research as an undergraduate, learning lab protocol. I believe that my write-ups for future anything will be greatly improved after having gone through this course.

> 75% State of the art equipment, caring and very knowledgeable professor.

> 75% It gives us the first-hand experiences of quantum optics.

**Question: What are the major weaknesses of this course? Please make suggestions for improvement.**

> 75% I feel like it needs to get bigger! While the small group was fantastic, I wish that more people would become involved so that it gains the momentum and attention it deserves!

> 75% Big groups is definitely a negative in the lab. I understand the professor had to be with us in the lab most of the time because of the research equipment, but without her presence, the TA made a very good job ensuring the students’ and equipments’ safety. Smaller groups would definitely help, more hands on time for each person. There 5 students in this course and we all did the same presentation, with the same experimental data. In the future, I believe it could be more beneficial if each student focuses on one lab, or make the presentations in Groups. Lastly, Assign the essay earlier in the semester. Last week of the semester just for this class, there was a final, presentation, essay, and lab 3 and 4 due.

**Question: Comments:**

LUKISHOVA > 75% There was never a time when she was unable to answer a question or approach it in a way that would make sense. Her labs were built so that we learned as we went, and when we fully understood how to handle the experiment, we were able to do it practically all by ourselves. In other words: we were taught, we learned it, and we excelled. Doctor Lukishova had an extreme impact on that happening.

LUKISHOVA > 75% Professor Lukishova took part in all the experiments with students. First, she would ask how much do we know about the exam, and then she show us how to do, and let us do it ourselves one by one. Every students are encoraged to do the experiments and ask questions. Besides the manual, she also gave lectures, which cover wider information about the lab which are very helpful.

**Question: Comments:**

LUKISHOVA > 75% I had a very vague understanding of what all the topics we touched on were, and even less of how it could be at all practical. Now, I can speak better on each of them then any of my colleagues. Not to mention, I have always had an interest in what the next "big thing" has been, and this whole course is based on what IS going to be the future of practically all technology. It was very eye-opening and exciting to work on such material. I hope I get to do it again in the future.

LUKISHOVA > 75% She made it look easy.

LUKISHOVA > 75% It is very free in this class. Whenever you have questions, we can discuss with the Professor. And no intense pressure about assignments and exam, because we usually have enough time, and we can improve them. So it makes me more relax to do it, and be willing to pay more efforts to get a higher score.

**Question: Comments:**

LUKISHOVA > 75% Thanks again. Not only was it fun and entertaining most of the time, but the experience I have gained really excites me. I truly believe I have finally learned something from taking a course.

LUKISHOVA > 75% I greatly recomend this course for students who are interested in quantum and quantum optics.

**Question: Comments:**

LUKISHOVA > 75% She says it best: we are students, we are learning, don’t be afraid to get anything wrong, you must try and learn. I wish every professor / teacher / mentor, whatEVER had this mentality towards passing knowledge on. It was incredibly easy to learn everything from Doctor Lukishova because she understood that we were, well, just students and just gaining the abilities to discern what is actually going on. She cared an almost ridiculous amount about how well we took on the material. It was awesome to have a teacher really be there every step of the way and make sure that we got every inch of material.

LUKISHOVA > 75% Meetings were easy to set, and will meet with you whenever you need. She is a very caring instructor, she insures that everyone understands the material before moving on.

LUKISHOVA > 75% My classmates and I always discussed with Professor Lukishova. She often inspired students to ask questions.

**Question: What are the major strengths of this instructor?**
<p>| LUKISHOVA | &gt; 75% | She cared extremely about our learning, not about our passing the class, our absorbing the material that she put in front of us. It was inspiring to be around someone that had such care for their work that they wanted to teach us so fully. Loved it! Thank you so much. |
| LUKISHOVA | &gt; 75% | knowledgeable, caring, fair. |
| LUKISHOVA | &gt; 75% | Professor Lukishova is very professional in this research area. Furthermore, she knows how to teach well and she understands students very much. |
|         |       | <strong>Question: What are the major weaknesses of this instructor? Please make suggestions for improvement.</strong> |
| LUKISHOVA | &gt; 75% | To cite a weakness would be a flaw in itself. I had NO problems all semester and find it hard to even fathom that someone would have a problem with how she conducted everything. |
| LUKISHOVA | &gt; 75% | organization, especially with due dates. |
|         |       | <strong>Question: If there are any other further comments you would like to make about this course, please do so in the space provided below.</strong> |
| LUKISHOVA | &gt; 75% | I am going to parade the need for this course to be taken around to everyone. Every underclassmen I know better be signed up. I would be very upset if this course went unnoticed for any longer! |</p>
<table>
<thead>
<tr>
<th>Question Text</th>
<th>N</th>
<th>Top Two</th>
<th>Avg</th>
<th>Major</th>
<th>Elective</th>
<th>Other</th>
<th>Uncertain</th>
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<tbody>
<tr>
<td>Status of course</td>
<td>4</td>
<td>100%</td>
<td>5</td>
<td>100%</td>
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<td>Class year</td>
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<td>0%</td>
<td>5</td>
<td>0%</td>
<td>0%</td>
<td>75%</td>
<td>25%</td>
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<tr>
<td>Involvement</td>
<td>4</td>
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<td>5</td>
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<tr>
<td>Student increase knowledge</td>
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<td>5</td>
<td>100%</td>
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<tr>
<td>Rate yourself in course</td>
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<td>100%</td>
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<tr>
<td>Syllabus describe course content</td>
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<td>5</td>
<td>100%</td>
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<tr>
<td>Readings were important in my learning of the course</td>
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<tr>
<td>Did assignments and exams support objectives</td>
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<td>5</td>
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<tr>
<td>Overall course rating</td>
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<tr>
<td>Responsiveness (LUKISHOVA)</td>
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<tr>
<td>Effectiveness (LUKISHOVA)</td>
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<td>Have a stronger interest in this subject because of this instructor (LUKISHOVA)</td>
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<td>Overall instructor rating (LUKISHOVA)</td>
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