# CCLI-PHASE I: QUANTUM OPTICS LABORATORY FOR THE UNDERGRADUATE CURRICULUM - TEACHING QUANTUM MECHANICS WITH PHOTON COUNTING INSTRUMENTATION


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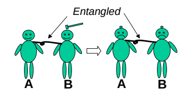
This advanced optics teaching laboratory course exposes students to *cutting-edge* photon counting instrumentation with applications ranging from quantum information (quantum computation and quantum cryptography) to biotechnology and medicine. To disseminate these materials we are working to incorporate them into a number of courses at various levels. This flexibility will make these laboratories appropriate to a wide range of educational institutions.


## ADVANCED LABORATORY COURSE CONSISTS OF FOUR EXPERIMENTS

### LAB. 1. ENTANGLEMENT AND BELL'S INEQUALITIES

Particles are called ENTANGLED if their state cannot be factored into single-particle states. Any measurements performed on first particle would change the state of second particle, no matter how far apart they may be.



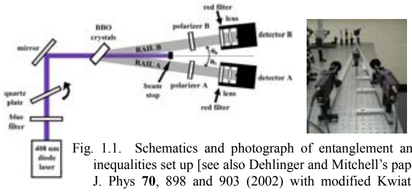
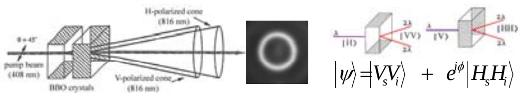




Fig. 1.1. Schematics and photograph of entanglement and Bell's inequalities set up [see also Dehlinger and Mitchell's papers, Am. J. Phys **70**, 898 and 903 (2002) with modified Kwiat's initial experiment for the undergraduate laboratory]. In this experiment two single-photon counting detectors A and B and a PC counter board are used to measure coincidence counts at various angles α and β of linear polarizers A and B placed in front of each detector.




$$|\psi\rangle = |V_s V_i\rangle + e^{i\phi}|H_s H_i\rangle$$

Fig. 1.2. Spontaneous parametric down conversion in two type-I BBO crystals mounted back-to-back, at 90º with respect to each other. Photons with wavelength 2λ are emitted within the cones. Phase shift ϕ is introduced by a crystal birefringence.

BELL'S INEQUALITY is valid for classical objects

$$S = E(a,b) - E(a,b') + E(a',b) + E(a',b') \leq 2$$

We calculate Bell's inequality for

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

To investigate an entangled state from two parametric down converted photons we select an incident polarization angle θ = 45º and compensate a phase shift ϕ using a quartz plate.

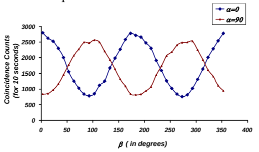



Fig. 1.3. Experimental polarization correlation as a proof of entanglement. Coincidence counts dependence on the polarization angle β in one of the arms of a parametric down conversion setup [~ $\cos^2(\alpha-\beta)$ for entangled photons]. Angles α are fixed. Incident laser power is ~ 3 mW.

The above calculation of S requires a total of sixteen coincidence measurements (N), at polarization angles α and β:

| α | β | α | β | α | β | α | β |
|---|---|---|---|---|---|---|---|
| -45 | -22.5 | 0 | -22.5 | 45 | -22.5 | 90 | -22.5 |
| -45 | 22.5 | 0 | 22.5 | 45 | 22.5 | 90 | 22.5 |
| -45 | 67.5 | 0 | 67.5 | 45 | 67.5 | 90 | 67.5 |
| -45 | 112.5 | 0 | 112.5 | 45 | 112.5 | 90 | 112.5 |

After collecting data we obtained *S* = 2.65. It is a clear confirmation of Bell's inequality violation and evidence of nonclassical behavior of downconverted photons.

### LAB. 2. SINGLE-PHOTON INTERFERENCE (Young's double-slit and Mach-Zehnder interferometer)

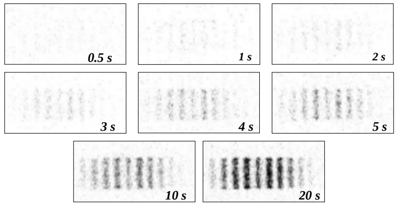



Fig. 2.1. Young's double slit experiment shows wave-particle duality. Measurements were made with electron-multiplying, cooled CCD camera iXon of Andor Technologies.

Mach-Zehnder interferometer (Fig. 2.2) is used for the demonstration of a single-photon interference after removing "which-way" information (identification of the path).

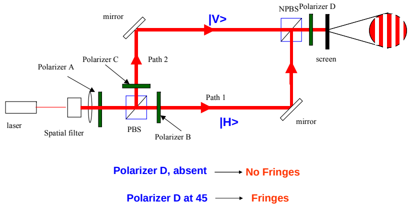



Fig. 2.2. Mach-Zehnder interferometer schematics for "which-way" experiment. [See also Schneider and LaPuma,'s paper, Am. J. Phys., **70**, 266 (2002)].

### LAB. 3. CONFOCAL MICROSCOPE IMAGING OF SINGLE-EMITTER FLUORESCENCE

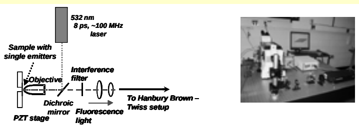



Fig. 3.1. Schematics and photograph of confocal microscope for single-emitter fluorescence microscopy.

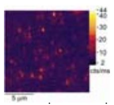


Fig. 3.2. A typical confocal fluorescence microscope image of a single colloidal CdSe quantum dots in a 1-D photonic bandgap chiral liquid crystal host under 6 ps pulse duration, 76 MHz pulse repetition rate excitation at 532-nm. Maximum fluorescence wavelength is 580 nm.

### LAB. 4. HANBURY BROWN AND TWISS SETUP. PHOTON ANTIBUNCHING

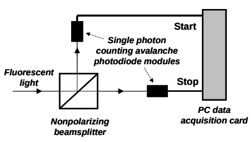



Fig. 4.1. Hanbury Brown and Twiss experimental setup for fluorescence antibunching measurements.

The second order correlation function of an optical field $g^{(2)}(t)$ that characterizes the difference between a single-photon source and a classical source should have a minimum at time t=0 (in an ideal case $g^{(2)}(0) = 0$), indicating the absence of photon pairs, i.e., *antibunching* .

At a low photon count rate $g^{(2)}(t)$ is proportional to a coincidence count rate measured by a PC card TimeHarp200.

Antibunching is a proof of a single-photon nature of a light source.

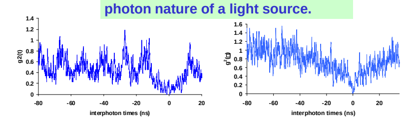



Fig. 4.2. Histogram of $g^{(2)}(t)$ demonstrating fluorescence antibunching of single colloidal quantum dot: left – for a PbSe quantum dot on a bare glass slip (λ = 850 nm) under pulsed laser excitation; right - for a CdSeTe quantum dot in a 1-D photonic bandgap cholesteric liquid crystal host (λ=700 nm, fluorescence lifetime of this quantum dot is higher than the time interval between two laser pulses).

## EVALUATION OF STUDENTS' KNOWLEDGE AND LABORATORY COURSE SUCCESS (Fall 2007)

**1. Formative evaluation** was carried out by six students enrolled in the laboratory course. 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 that **indicates the success of the course**. The main improvements of the course should be less intensive homework tasks. Some students wanted to build experimental set-ups from scratch.

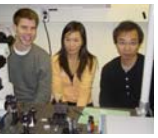
**2. Summative evaluation** was accomplished by two ways: (1) using different questionnaires (without grading) and (2) using the grades for each lab. Two teaching assistants helped in summative evaluation. For instance, using questionnaire with 36 questions on photon quantum mechanics showed that one half students answered correctly more than 75% of questions, 70% of students answered correctly more than 70% of questions and all students answered correctly more than 60% of questions. **It shows the success in students' learning.**

**3. Students' mastery** in photon-counting instrumentation showed that 50% 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.

**4. For communication skills development** students were divided into groups (two or three students in each group depending on particular lab). Each group of students presented a single report written by all group members **although students within each group can received different grades for the lab**. The grade also depended on students' activity and knowledge during the whole lab. Before each lab students were asked to and were able to ask their instructor any questions.

**5. To recognize and analyze alternative explanations and models** students were asked to write the essays on alternative technologies to single-photon sources based on single colloidal quantum dots.

**6. Nearly 50 students benefited from these laboratory experiments.** In addition to enrolled students for 4-credit hour laboratory course and students building the quantum optical laboratory, 26 students of the course "Optics in the Information Age" (W. Knox) and a group of students of Colgate University visiting the Institute of Optics participated in the lecture-demonstration of these experiments.

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