QUANTUM OPTICS AND QUANTUM INFORMATION TEACHING LABORATORY COURSE

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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.

ADVANCED LABORATORY COURSE CONSISTS OF FOUR EXPERIMENTS

LAB. 1. ENTANGLEMENT AND BELL'S INEQUALITIES

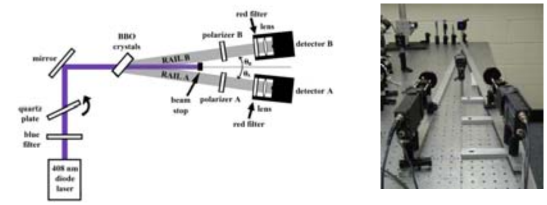
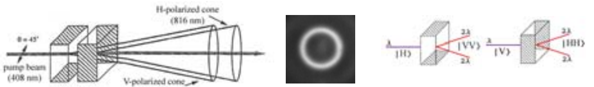


Fig. 1.1. Schematics and photograph of entanglement and Bell's inequalities set up [see also Dehlinger and Mitchell's papers, Am. J. Phys **70**, 898 and 903 (2002) with modified Kwiat's initial experiment for the undergraduate laboratory]. In this experiment two single-photon counting detectors A and 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 (image in the center was made with an argon ion laser excitation with λ = 363.8 nm and incident power ~ 100 mW using EM-CCD camera). Phase shift ϕ is introduced by a crystal birefringence.

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.

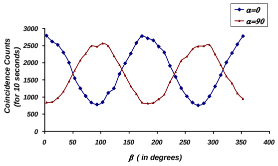


Fig. 1.3. Experimental polarization correlation as a proof of entanglement. Coincidence counts dependence on the polarization angle β in one of the arms of a parametric down conversion setup [~ cos² (α-β) for entangled photons]. Angles α are fixed. Incident laser power of a 408 nm diode laser is ~ 3 mW.

BELL'S INEQUALITY in the form of Clauser-Holt-Shimony-Horne

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

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

We calculate Bell's inequality for

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

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 students 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)

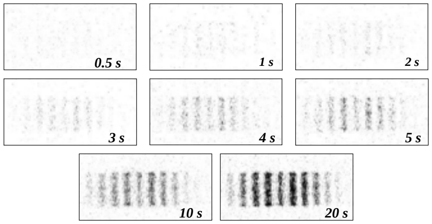
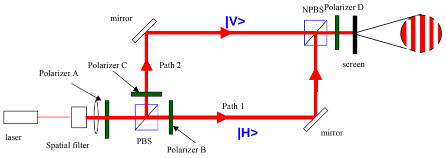


Fig. 2.1. Young's double slit experiment shows wave-particle duality. Measurements were made with electron-multiplying, cooled CCD camera iXon of Andor Technologies.

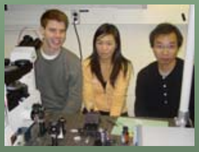
Mach-Zehnder interferometer (Fig. 2.2) is used for the demonstration of a single-photon interference after removing "which-way" information (identification of the path).



Polarizer D, absent → **No Fringes**

Polarizer D at 45 → **Fringes**

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

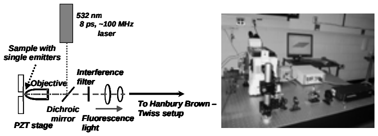


Fig. 3.1. Schematics and photograph of confocal microscope for single-emitter fluorescence microscopy.

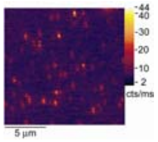


Fig. 3.2. A typical confocal fluorescence microscope image of a single colloidal CdSe quantum dots in a 1-D photonic bandgap chiral liquid crystal host under 6 ps pulse duration, 76 MHz pulse repetition rate excitation at 532-nm. Maximum fluorescence wavelength is 580 nm.

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

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

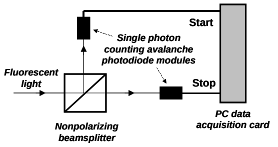


Fig. 4.1. Hanbury Brown and Twiss experimental setup for fluorescence antibunching measurements.

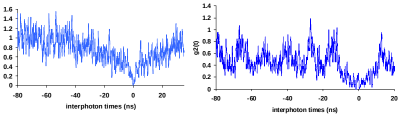


Fig. 4.2. Histograms of $g^{(2)}(t)$ demonstrating fluorescence antibunching of single colloidal quantum dot under pulsed laser excitation: left – for a CdSeTe quantum dot in a 1-D photonic bandgap cholesteric liquid crystal host (λ=705 nm, fluorescence lifetime of this quantum dot is longer than the time interval between two laser pulses); right - for a PbSe quantum dot on a bare glass slip (λ = 850 nm).

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