Experiment 6 — Quantum Mechanics and Quantum Optics: Introduction

References

The Quantum Challenge by G. Greenstein and A. G. Zajonc (1997, or 2nd edition 2005)
The first two chapters of this book set the stage for the test of the quantum nature of light. The book as a whole is an intriguing review of recent tests of quantum theory, and suggests many elaborate experiments with our setup – tests of Bell's inequality, quantum erasers, quantum coherence theory, etc. Strongly recommended background reading!

"The Nature of Light: What is a Photon?", *Optics and Photonics News Trends* Oct 2003.
This is a special issue of *OPN Trends* focusing on the current notion of a "photon". There are five articles by renowned experts in the field of quantum optics, and the one by Arthur Zajonc and another by Rodney Loudon are particularly relevant for us.

Introduction

The particle-wave duality of light has sparked heated debate throughout the history of science. In the early 20th century, it became clear that the particle-wave duality applied to "particles" as well as light, and this of course refueled the debate leading to even deeper controversy. Not only were scientists faced with the job of reconciling in one theory the aspects of Newton's particles and Maxwell's waves, but the whole notion of physical reality as described by the new quantum theory seemed to be dragged into the fray. The Einstein-Podolsky-Rosen paradox seemed to epitomize the difficulties that many scientists encountered in constructing an appropriate view of physical reality. Quantum theory certainly seems to be successful, but the word "strangeness" is now a popular term used to describe some of its predictions – and most of these predictions have been verified experimentally!

The setup associated with this experiment consists of a source of entangled photon pairs, some standard optical components, and four photon-counting silicon photodetectors. (See Fig. 4-1) A wide array of measurements can be performed with this equipment, including: (1) a confirmation of the quantum nature of the photon, i.e., light exists in quanta, (2) a study of single-photon interference, (3) a demonstration that photons are bosons, (4) a test of Bell's inequalities, and (5) a demonstration of a "quantum eraser".

Beginning in the Fall of 2005 and the Spring of 2006, students in Advanced Lab and Optics Lab have performed experiment (1) and confirmed the quantum nature of the photon, though it is an experiment that has been recently enhanced by new, faster data acquisition hardware (field programmable gate array - FPGA) that makes possible new measurements with classical light sources that serve as important control experiments. The measurement exploits the properties of a pair of entangled photons and employs time-coincidence techniques to show that a photon incident upon a beamsplitter is either

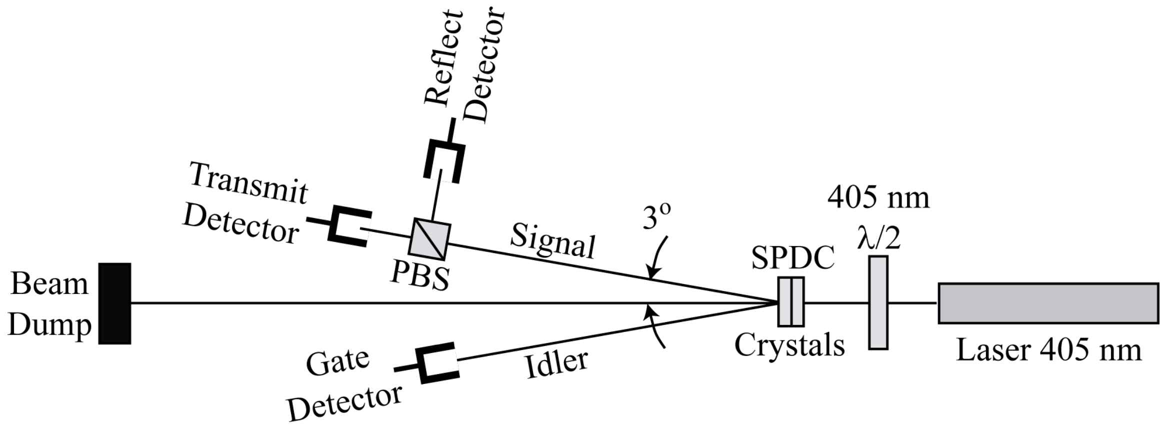

Fig. 4-1. Experimental setup for the study of the quantum nature of light. (PBS = polarizing beamsplitter; SPDC = spontaneous parametric down-conversion.) According to quantum theory, a signal photon incident upon the polarizing beamsplitter (PBS) is either transmitted or reflected, so no GTR triple-coincidence counts should be recorded.

transmitted or reflected but does NOT go in both directions as classical electromagnetic theory would predict. The experiment goes to the heart of the field of photon statistics and quantum optics.

Students have also performed experiment (4) by examining a situation in which the predictions of quantum mechanics are confirmed but those of hidden variable theories are clearly violated. The entangled polarization state of photon pairs is produced in the "spontaneous parametric down-conversion" process which forms the core of the "single photon source", a key component of the experimental setup. The experiment is very reminiscent of the Einstein-Rosen-Podolsky (EPR) paradox that started all the intellectual hubbub in the mid-20th century. These Bell inequality tests have been performed several times, though recently we have acquired a "pre-compensation" quartz crystal that should improve the "purity" of the entangled polarization state of photon pairs and hence accentuate the failure of hidden variable theories to account for the measurements. A similar pre-compensation crystal produces highly entangled photon states in the Lynn research lab (see Julien Devin's senior thesis, 2012), but so far we have not succeeded in reproducing that result in the optics/advanced lab setup. Carefully reviewing the theory, the crystal specifications, and the experimental setup should enable us to solve this puzzle!

Finally, in the Fall of 2010, Advanced Lab students assembled an optical setup that comprises (5) a quantum eraser, and preliminary results were dramatically successful! This experiment includes an interferometer in the path of the "signal" photon which produces interference fringes, so (2) single photon interference is involved in this experiment as a delightful bonus! The measurement consists of first demonstrating fringes at the output of an interferometer in the "signal" photon path, with the polarization optics in the "idler" photon path having appropriate settings. Then a half-wave plate in the idler photon path is rotated by 22.5°, and suddenly the fringes generated in the "signal" photon path disappear because polarization now offers *which-way* information on a signal photon's path through the interferometer. When the idler half-wave plate is rotated back to its original position, the which-way information is "erased," and fringes reappear. The finges are controlled by an adjustment that is potentially space-like separated from the fringe measurement! A DC servo motor actuator has been installed to automate the collection of fringes, and fringes have been observed with the revised setup. However, the fringes do not entirely disappear, so this experiment offers the challenge of uncovering the flaw(s) in the setup and successfully observing the complete disappearance and recovery of fringes to confirm the predictions of quantum mechanics.

Choosing one of three experimental paths

You must decide which of these three types of measurements to pursue:

i. the confirmation of the quantum nature of light

ii. tests of Bell's inequalities (with possible investigation of the pre-compensation crystal), or

iii. demonstration of a quantum eraser. You can't do all three, and you can't go wrong no matter which you choose! Each experimental path is described in more detail in a sequel document accessible wherever you found this introductory document. Enjoy the journey!