

Experiment 6 - Quantum Mechanics and Quantum Optics: The Quantum Nature of Light

References:

- “Observing the quantum behavior of light in an undergraduate laboratory,” by J. J. Thorn, M. S. Neel, V. W. Donato, G. S. Bergreen, R. E. Davies, and M. Beck, *American Journal of Physics* **72**(9) 1210-1219 (2004). This paper from Mark Beck’s group at Whitman College describes the experiment that Adam Pivonka and Tera Bell replicated in 2004-2005 to confirm the existence of quanta of light. In fact, Prof. Beck generously guided us as we purchased the components of our current experimental setup, and he also made available to us everything on his website, including the LabVIEW VIs that we use to acquire data. This paper is a MUST read!
- “Studying the Quantum Nature of Light,” by Adam Pivonka, senior thesis, May 2005. A copy is placed with the lab reference material, and an electronic version is available on the course Sakai site. Adam describes the use of the setup to confirm the quantum nature of the photon. ALL of the details are there!
- “Comparing measurements of $g^{(2)}(0)$ performed with different coincidence detection techniques,” by M. Beck, *J. Opt. Soc. Am. B* **24**, 2972-2978 (2007). This paper by Mark Beck is particularly useful if you are attempting to do a control experiment, measuring the autocorrelation function for a classical source of light. The paper explains how the limitations of our NIM counting and coincidence electronics influence the count rates and render them difficult to interpret when working with a very high single-detector rate (roughly above 50,000/s); the Whitman College group ultimately adopted FPGA data acquisition modules to overcome these limitations, and so have we! An FPGA module is available and awaits use by Optics Lab and Advanced Lab students to measure $g^{(2)}(0)$ for a classical source (as well as a single-photon source).

Introduction

Adam Pivonka and Tera Bell (HMC '05) pursued a study of the quantum nature of light as their senior research project. They used coincidence techniques to show that a photon incident upon a beam splitter is either transmitted or reflected, but not both at the same time! They pointed out that classical theories of the electromagnetic field cannot explain this result. In fact, even a semi-classical theory, in which atoms are quantized and the EM field is described as a classical wave, predicts a strong correlation between transmitted and reflected beams, or at least no correlation, rather than the strong anti-correlation observed (a photon counted in the transmitted beam means NO count in the reflected beam).

The work of Adam and Tera has been repeated and confirmed by members of the Advanced Lab and Optics Lab courses, and also by Andy Fischer and Travis McQueen (HMC '06) as part of their senior thesis project. In addition, many participants in Optics Lab have conducted control experiments to demonstrate, as well as possible with our

current NIM electronics, that our measurement scheme when applied to a classical light source yields no correlation rather than anti-correlation between the transmitted and reflected beams (see the 2007 paper by Beck). Extensive work has been performed on the data acquisition hardware in this experiment, and there is now the possibility of employing FPGA (Field Programmable Gate Array) modules to collect data with photon count rates at least 10 times higher. These higher count rates facilitate measurements of $g^{(2)}(0)$ for a classical light source with far better statistics and precision.

I. Demonstrating the Quantum Nature of Light

The conceptual scheme of our experiment is sketched in Fig. 6-1. We assume for the moment that we have a reliable source of single photons. Using this light source, we throw a steady stream of single photons at a beamsplitting cube. Photon-counting detectors are placed at the transmission and reflection outputs of the beamsplitter. (See Fig. 6-2 for a photo of the experimental equipment. The detectors are housed in a light-tight box, and the photons are led to them by multimode optical fiber.) If the photon is really an indivisible particle, then either the transmission detector will record a photon, or the reflection detector will record a photon, but not both simultaneously! If the beamsplitter has a 50%-50% splitting ratio, then half the time the transmission detector records the photon and half the time the reflection detector records the count. This is in sharp contrast with the classical view of this experiment.

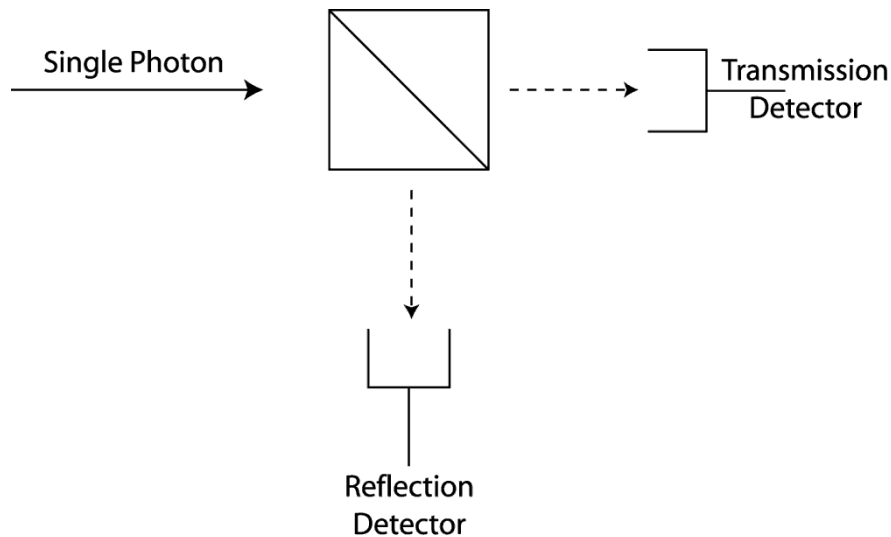


Fig. 6-1. A single photon is incident upon a beamsplitting cube, and photon-counting detectors look for a photon at the transmitted and reflected outputs.

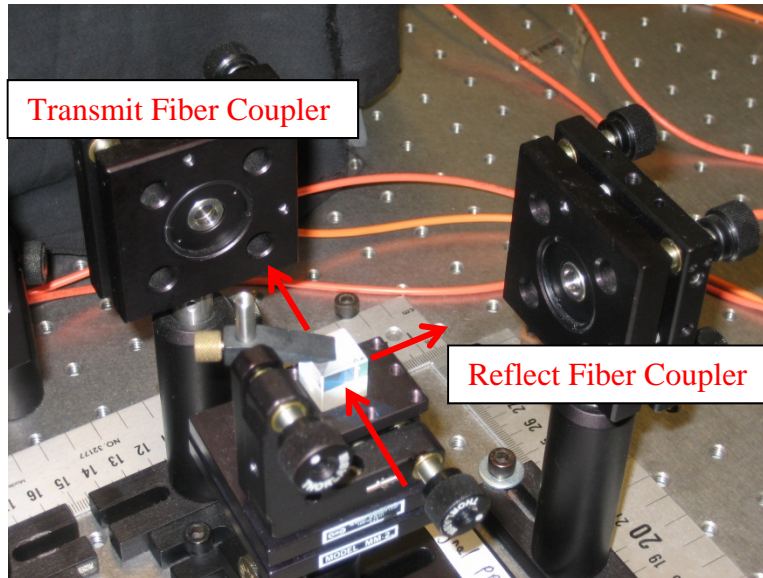


Fig. 6-2. Photograph of the polarization beamsplitter in the signal photon path. A vertically polarized photon incident upon the beamsplitting cube is reflected toward the "Reflect" fiber coupler, while a horizontally polarized photon is transmitted to the "Transmit" fiber coupler.

Classical Theory The correlation between the transmitted and reflected intensities can be characterized quantitatively by the degree of second order coherence of the electric fields at the two outputs:

$$g_{TR}^{(2)}(0) = \frac{\langle I_T(t) I_R(t) \rangle}{\langle I_T(t) \rangle \langle I_R(t) \rangle} \quad (6-1)$$

We have evaluated $g_{TR}^{(2)}(\tau)$, sometimes called the “normalized intensity correlation function,” at a time delay τ of zero, since we will be looking at the transmitted and reflected outputs at the same time. The angle brackets in Eqn. (6-1) indicate that the time average is taken. Notice that the numerator is the time average of the product of the transmitted and reflected intensities. As mentioned above, if we do not expect the transmission and reflection detectors to produce outputs at the same time, then the numerator will be zero. In contrast, if we define transmission and reflection coefficients, T and R , then the transmitted and reflected intensities will be $I_T = T I_0$ and $I_R = R I_0$, where I_0 is the incident intensity. In our classical view, we regard the incident intensity as a continuous variable, and a portion is transmitted and a portion reflected, so that Eqn. (6-1) becomes

$$g_{TR}^{(2)}(0) = \frac{\langle I_T(t) I_R(t) \rangle}{\langle I_T(t) \rangle \langle I_R(t) \rangle} = \frac{\langle T I_0(t) R I_0(t) \rangle}{\langle T I_0(t) \rangle \langle R I_0(t) \rangle} = \frac{\langle [I_0(t)]^2 \rangle}{\langle I_0(t) \rangle^2} \quad (6-2)$$

The Cauchy-Schwartz inequality implies that $\langle [I_0(t)]^2 \rangle \geq \langle I_0(t) \rangle^2$, so that classically we have

$$g_{TR}^{(2)}(0) = \frac{\langle I_T(t) I_R(t) \rangle}{\langle I_T(t) \rangle \langle I_R(t) \rangle} = \frac{\langle [I_0(t)]^2 \rangle}{\langle I_0(t) \rangle^2} \geq 1 \quad (\text{Classical View}) \quad (6-3)$$

The Whitman College group (Thorn et al., 2004) and also Adam Pivonka (HMC senior thesis) have shown that Eqn. (6-3) holds also in the semi-classical view. In this theory, the energy states of atoms are quantized so that energy is absorbed from the electromagnetic field in quanta, but the electromagnetic field itself is treated classically as a continuous field.

Quantum Theory When the electromagnetic field is quantized (Quantum Electrodynamics or QED), the transmitted and reflected intensities in Eqn. (6-1) become operators (denoted with hats):

$$g_{TR}^{(2)}(0) = \frac{\langle : \hat{I}_T \hat{I}_R : \rangle}{\langle \hat{I}_T \rangle \langle \hat{I}_R \rangle} \quad (6-4)$$

In Eqn. (6-4), the colons indicate normal ordering of the creation and annihilation operators that are implicit in the intensity operators. The Whitman group and Adam Pivonka present a careful evaluation of Eqn. (6-4) with the result:

$$g_{TR}^{(2)}(0) = \frac{\langle : \hat{I}_T \hat{I}_R : \rangle}{\langle \hat{I}_T \rangle \langle \hat{I}_R \rangle} = 0 \quad (\text{Quantum View}) \quad (6-5)$$

We shall not repeat their derivation here, but simply note that that the result agrees with our intuitive expectation that a particle-like photon will be detected by the transmission detector or by the reflection detector, but not by both at the same time.

Theory Summary When the transmitted intensity is completely uncorrelated with the reflected intensity, the average of the product in the numerator of Eqn. (6-1) is equal to the product of the averages, and $g_{TR}^{(2)}(0) = 1$. This is the case for laser sources. It is also true that photons are distributed in a laser beam such that the number of photons detected in a time interval Δt is distributed according to the Poisson distribution. (See Eqn. (6-6) below.)

When the transmitted intensity is positively correlated with the reflected intensity, so that both detectors are likely to be detecting photons at the same time (in bunches), then $g_{TR}^{(2)}(0) > 1$. This is the case for “thermal” or “chaotic” sources like fluorescent lights or incandescent light bulbs. If the detectors are fast enough to follow the fluctuations

of these sources, $g_{TR}^{(2)}(0) = 2$. In this case, the numbers of photons detected in a time interval Δt are distributed according to the Bose-Einstein distribution.

Only when the transmitted intensity is perfectly *anti*-correlated with the reflected intensity does $g_{TR}^{(2)}(0) = 0$. In this truly quantum case, the photon distribution is called “sub-Poissonian” because the variance of the number of photons detected in a time interval Δt is less than the mean number.

Single Photon Light Sources Up to this point we have assumed that we possess a single-photon light source with which we can launch a steady stream of photons toward the beamsplitting cube in Figs. 6-1 and 6-2. It is tempting to imagine constructing such a light source simply by attenuating a laser beam so that, on average, only one photon is in the vicinity of the beamsplitter at any given time. The probability of detecting n laser photons in a time interval Δt is given by the Poisson distribution

$$P(n, \Delta t) = \frac{\langle n \rangle^n}{n!} e^{-\langle n \rangle} \quad (6-6)$$

where $\langle n \rangle$ is the average number of photons recorded in Δt . Using Eqn. (6-6), it is easy to show that the ratio of probabilities of detecting 2 photons to just 1 photon in a time interval Δt is

$$\frac{P(2, \Delta t)}{P(1, \Delta t)} = \frac{\langle n \rangle}{2} \quad (6-7)$$

If Δt is the time taken by light to travel through the vicinity of the beamsplitter, and if the laser is attenuated so that $\langle n \rangle \ll 1$, then there will be usually just one photon in the vicinity of the beamsplitter. However, the probability of having any photons at all in the vicinity of the beamsplitter is now small, since $P(1, \Delta t) \approx \langle n \rangle \ll 1$. In fact, $g_{TR}^{(2)}(0)$ is normalized by the average count rates in such a way that its value would still be 1 for an attenuated laser beam! We clearly need, not just an attenuated classical light source, but a non-classical single-photon light source if we are to demonstrate the particle nature of the photon.

II. The Experimental Setup

Our experimental setup for studying the quantum nature of light is sketched in Fig. 6-3. The entangled photon-pair source comprises a 50 mW violet laser (405 nm) illuminating a pair of barium borate (BBO) crystals cut to facilitate type-I spontaneous parametric down-conversion (SPDC). In this nonlinear process an occasional incident 405-nm photon is converted into a pair of 810 nm photons with linear polarization orthogonal to the linear polarization of the incident beam. The two BBO crystals are cut at the same angle to their optic axes but then oriented at 90° to one another, so that the two different crystals yield SPDC photons with orthogonal polarizations. The half-wave plate provides a means for rotating the polarization of the incident beam so that roughly equal numbers of horizontally and vertically polarized 810 nm photons are produced in the SPDC process. Conservation of momentum and energy imposes constraints on the two 810-nm photons, so that they are entangled in energy, direction, and polarization.

One of the 810-nm photons is called the “idler” photon and is used as a gate for coincidence circuitry, while the other 810-nm photon is called the “signal” photon and is directed toward a beamsplitter. In effect, gating with the idler photon allows us to conduct measurements in the signal path only when we know there happens to be a single photon in that path. This type of setup is known as an *a posteriori* source of single photons, as opposed to the desirable but technically daunting *a priori* source which would produce single photons on demand.

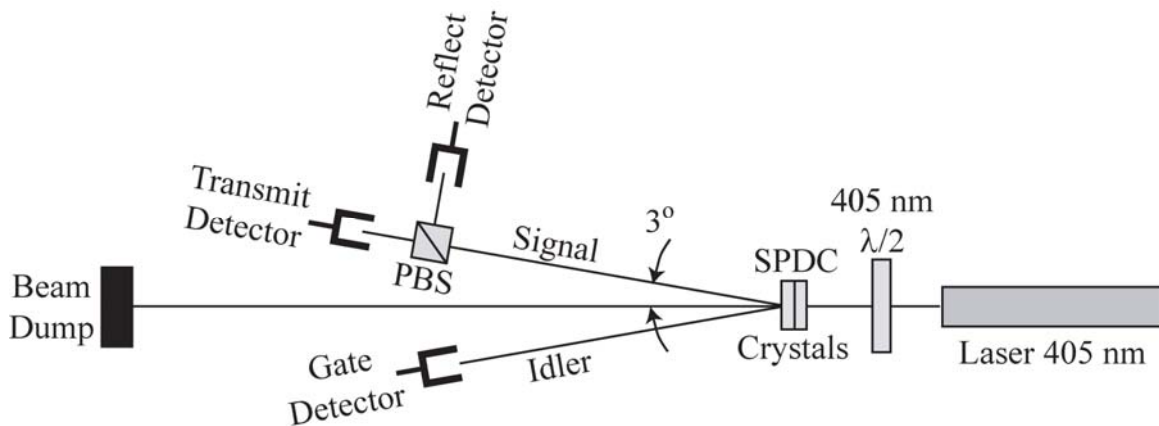


Fig. 6-3. Experimental setup for the study of the quantum nature of light. (PBS = polarizing beamsplitter; SPDC = spontaneous parametric down-conversion.)

The idler and signal photons are captured by lens/optical-fiber combinations called “fiber couplers”. The optical fiber transports the photons to silicon avalanche photodiodes (APDs) that are capable of detecting single photons with 60% quantum efficiency. The 20-ns-wide TTL pulses from the photodetectors are sent to three time-to-amplitude/single-channel-analyzer (TAC/SCA) modules that record two-way and three-

way coincidences. The two-way coincidences are between the gate and transmission detectors (GT) and between the gate and reflection detectors (GR). The three-way coincidences involve all three detectors (GTR). See Fig. 6-4 for a schematic of electrical connections.

It is important to understand the operation of the TAC/SCA modules. In fact, setup and understanding of these may well occupy you for more than one full lab session. Let us consider the GT TAC/SCA module, in which the gate pulse is connected to the START input and the transmission pulse is connected to the STOP input. The TAC circuitry generates an output pulse with an amplitude that is proportional to the delay between the START pulse and the STOP pulse. We have inserted a little extra cable in the transmission and reflection pathways (10 ft and 20 ft, respectively) so that the transmission pulse is conveniently delayed by ~ 15 ns, and the reflection pulse is delayed by ~ 30 ns. (Electrical signals travel at about 8 inches/ns (2×10^8 m/s) in the coax cable.) As a result, when gate and transmitted photons are received by the detectors simultaneously, the GT TAC circuitry outputs a 3- μ s-wide pulse with an amplitude of

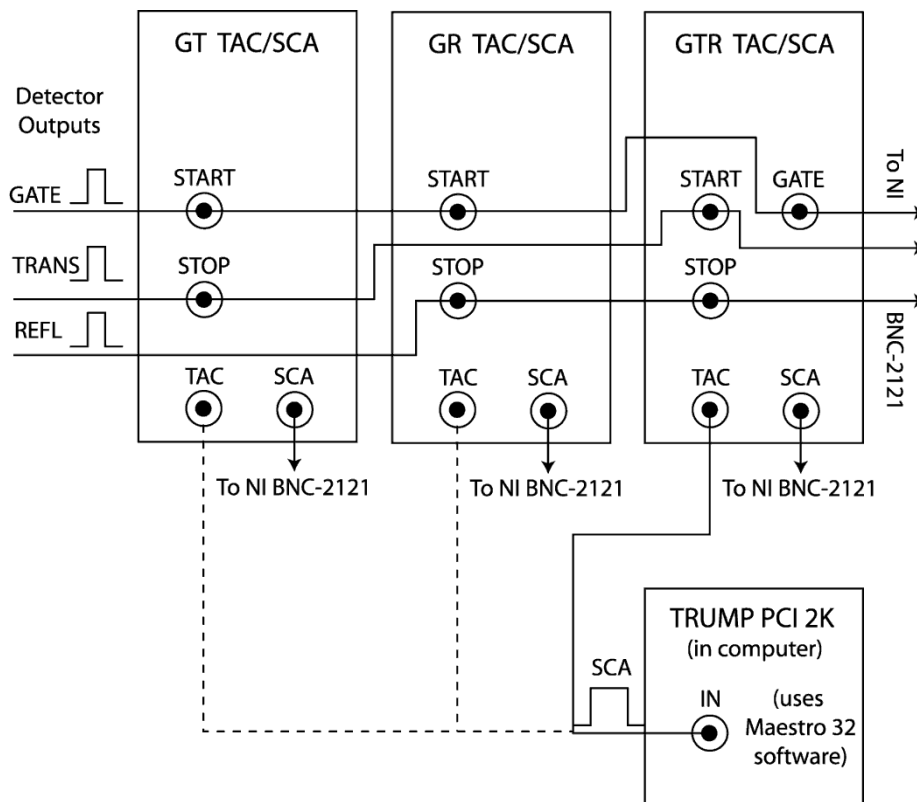


Fig. 6-4. Output pulses from the three detectors are routed to three Ortec 567 Time-to-Amplitude/Single-Channel-Analyzer (TAC/SCA) modules and to the National Instruments 6602 Counter/Timer board through the BNC-2121 Connector Accessory. See Fig. 6-5 for the connections to the BNC-2121 Connector Accessory. The TAC outputs are connected to the

Ortec TRUMP PCI 2K pulse height analyzer (PHA) board for analysis of the timing of the photon pulses using the Maestro 32 software.

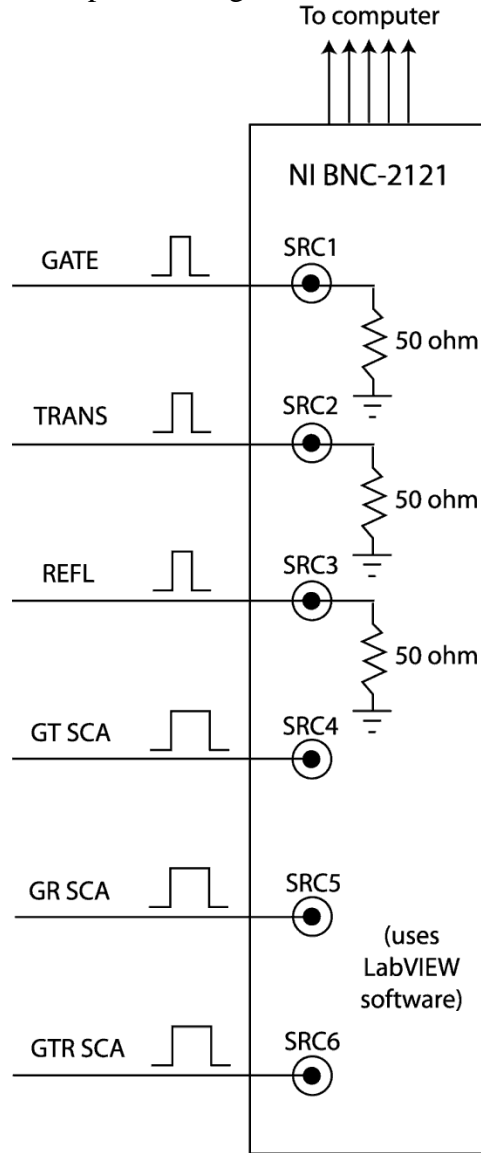


Fig. 6-5. Signals are routed by the National Instruments BNC-2121 connector accessory to the National Instruments 6602 Counter/Timer Board which is inserted into the chassis of the computer. The NI 6602 has 8 counters, and we use 6 of them. The board is controlled by LabVIEW software.

about 3.0 volts (10 volts corresponds to 50 ns delay, so 3 volts corresponds to 15 ns). The SCA circuitry on the GT module is set so that TAC pulses ranging from 2.6 to 3.4 volts will generate an SCA output pulse (about 3 μ s wide) which is then counted by the NI 6602 counter board. See Fig. 6-5 for a schematic of connections to 6 of 8 counters on the NI 6602 board. The TAC output, in addition to being passed internally to the SCA

circuitry, can be sent to the TRUMP PCI 2K pulse height analyzer (PHA) card. The Maestro 32 software can be used to examine the amplitudes of TAC pulses and hence the time delays between the START and STOP pulses, and this information greatly simplifies the setting of the window of the SCA.

How Can We Measure $g^{(2)}(0)$? We need to relate measurable count rates to the definition of $g_{TR}^{(2)}(0)$ in Eqn. (6-1). You can probably convince yourself of the following expression:

$$g_{TR}^{(2)}(0) = \frac{\langle I_T(t)I_R(t) \rangle}{\langle I_T(t) \rangle \langle I_R(t) \rangle} = \frac{P_{TR}}{P_T P_R} \quad (6-8)$$

Here P_{TR} is the probability of recording a transmitted photon and a reflected photon in the same time interval Δt , and P_T and P_R are the probabilities of recording a transmitted photon or a reflected photon in a time interval Δt , respectively. However, in order to implement our single photon source, we condition the recordings of transmitted and reflected photons on the reception of a simultaneous gate photon (idler photon). We must rewrite the expression in Eqn. (6-8) so that it is relevant to our use of a single photon source:

$$g_{TR}^{(2)}(0) = \frac{\langle I_T(t)I_R(t) \rangle}{\langle I_T(t) \rangle \langle I_R(t) \rangle} = \frac{P_{GTR}}{P_{GT} P_{GR}} \quad (6-9)$$

where, for example, P_{GTR} is the probability of recording counts in all three detectors in a time interval Δt . With a little more thought, you can probably convince yourself that these conditional probabilities can be expressed in terms of recorded counts:

$$P_{GT} = \frac{N_{GT}}{N_G} \quad P_{GR} = \frac{N_{GR}}{N_G} \quad P_{GTR} = \frac{N_{GTR}}{N_G} \quad (6-10)$$

where N_{GT} is the number of GT coincidence counts recorded in a given time interval, and N_G is the number of singles counts recorded by the gate detector in the same time interval. Three subscripts indicate triple coincidences. Combining Eqns. (6-9) and (6-10) we have

$$g_{TR}^{(2)}(0) = \frac{\langle I_T(t)I_R(t) \rangle}{\langle I_T(t) \rangle \langle I_R(t) \rangle} = \frac{P_{GTR}}{P_{GT} P_{GR}} = \frac{N_{GTR} N_G}{N_{GT} N_{GR}} \quad (6-11)$$

Our job then is to measure these coincidence counts and singles counts and discover if indeed our value for $g_{TR}^{(2)}(0)$ is close to zero as we would expect for a single photon source, or if it is nearer to 1.0 as we would expect from a classical perspective.

III. Measurements During the First Lab Meeting

You will want to begin your labwork by checking on optical alignment and instrument settings, and doing so will help to familiarize yourself with the experimental setup. But first a few words of caution:

**WEAR THE LASER SAFETY GOGGLES
WHEN YOU TURN ON THE BLUE LASER!!!!**

**TURN OFF THE ROOM LIGHTS
BEFORE POWERING ON THE PHOTODETECTORS!!**

The first cautionary note is for your own safety, and the second is for the protection of our photon-counting silicon avalanche photodiodes. The module of four detectors costs \$12 K!! On the other hand, *your eyes are priceless!!*

To begin, have your instructor or an experienced colleague show you how to mount the BBO crystals in their mirror mount. The crystals are hygroscopic (suck up moisture from the air), so we store them with desiccant in a container on the optical table when not in use. We also blow dry nitrogen gently across one face of the crystals while they are in use on the optical table. They are not severely hygroscopic, so don't stress out about it, but it is prudent to keep them in a dry atmosphere at all times. That's not too hard to do in a good lab in southern California! While your instructor or experienced colleague is still in the area, have them show you the long-pass filters and photodetector module in the light-tight box on the optical table. Then button everything up and get ready for the festivities!

Put your goggles on and pull the curtain around the experimental setup to protect others in the main lab area from stray laser reflections. Power ON the 405 nm laser. Adjust the BBO crystal mirror mount so that the back-reflection of the laser goes right back on itself (centered on the iris diaphragm). This should be a small adjustment. You will probably want to check the general alignment of the optical setup - the 405 nm laser beam should pass through the center of the iris diaphragm in front of the laser, and also through the iris diaphragm in front of the beam stop. But before making any adjustments to the alignment, please consult your instructor. Everything should already be fairly well aligned. If not, we will need to think carefully about how to proceed!

Power ON the NIM bin containing the TAC/SCA modules, and power ON the HP digital oscilloscope sitting on top of the NIM bin. Turn off all lights and darken the area as much as possible, and then use the flashlight to power ON the three power supplies for the photodetector module. You should disconnect the gate cable at the GTR TAC/SCA module and hook it up to the oscilloscope for viewing. The gate detector output should be 4 volts high and about 20 ns wide. To observe the pulse successfully you will need to terminate the coax cable with 50 ohms to prevent ringing (reflections up and down the cable). Reconnect the gate cable to the GTR TAC/SCA module. Notice that the ends of

the detector cables in this configuration are already terminated with 50 ohms just before they connect to the BNC-2121 input to the counter board (see Fig. 6-5).

Power ON the PC computer “Beck” and log in under the account name “quantum” and password “photon”. There should be a few sheets of instructions placed with the experimental setup. One sheet will help you use the Maestro 32 software to interface with the pulse height analyzer (PHA) card to check on the SCA windows, and another will help you use LabVIEW to record coincidence counts and singles counts. You should first open the LabVIEW program “Continuous Counter with 6 NIM Inputs” to observe single-channel and coincidence count rates and play around for a bit, performing reality checks. For example, you will want to block the laser beam and/or the fiber couplers and measure the detector dark counts. In complete darkness, these are about 300 to 600 counts/sec.

Check SCA windows for GT and GR coincidences To ensure that the experiment is working as intended, and to familiarize yourself with the coincidence-counting electronics, you should verify that the TAC/SCA modules are optimally configured to record GT and GR coincidences. First, locate the GT TAC/SCA module. Connect the TAC output to the PHA input cable, and use Maestro to observe a histogram of coincidence counts vs. time delay. The Maestro instruction sheet in the lab will guide you through the process of collecting this histogram and using it to set an appropriate SCA window.

Return the GT TAC/SCA electronics to their original configuration. Then locate the GR TAC/SCA and use Maestro and the PHA card to set the GR SCA window appropriately. Then return the GR TAC/SCA electronics to their original configuration as well.

Go back to LabVIEW and observe the GT and GR coincidence rates. With good optical alignment and optimal SCA windows, each coincidence rate should be around 150-200 coincidences per second. Save some data to a file to document your count rates.

IV. Testing the Quantum Nature of Light

When you are finally ready to measure $g_{TR}^{(2)}(0)$ for our single-photon source, there are a couple of checks on equipment that you should perform first. Assuming you believe that photons behave like indivisible particles, you probably expect to measure no triple coincidences (GTR). There are lots of ways to measure zero. For example, you might just forget to power ON the photodetectors. That’ll do it! You get the point. It is important to perform independent checks on the performance of the GTR TAC/SCA module to make sure that if there *were* triple coincidences, the GTR TAC/SCA module would record them.

Our use of the GTR TAC/SCA module is different from the GT and GR setups because for the GTR triple coincidence, we are employing the GATE input on the START circuitry. As indicated in Fig. 6-4, the idler photon pulse (gate pulse) is connected to the GATE input of the START circuitry, so that an idler photon will enable the START circuitry to register a START pulse from the transmission detector, which in turn allows a

pulse from the reflection detector to register a STOP pulse and initiate TAC and SCA output pulses. We must be sure that this GATE input on the START circuitry is working properly. Also, we must be sure that the GTR SCA window is set properly to select a TAC pulse that corresponds to the actual time delay between a transmission detector pulse and a reflection detector pulse. We mentioned in Section II that we have inserted extra cabling in the transmission and reflection paths (10 ft and 20 ft, respectively) that results in a delay of ~ 15 ns for the transmission pulse and ~ 30 ns for the reflection pulse, relative to the gate pulse. That means that the reflection pulse should be delayed by ~ 15 ns relative to the transmission pulse. Hence we would expect to see GTR TAC pulses of ~ 3 volts, and the SCA window should be centered at about 3 volts (since $\frac{15 \text{ ns}}{50 \text{ ns}} * 10 \text{ V} \approx 3 \text{ V}$).

Make Sure the GATE Input Works on the START Circuitry Keep the gate pulse connected to the GATE input of the START circuitry and the transmission pulse connected to the START input of the GTR TAC/SCA module. However, disconnect the reflection pulse from the STOP input, and disconnect the transmission pulse from everything it goes through downstream of the START input. Instead, lead the transmission pulse through a 10 ft. cable from the START input to the STOP input (don't forget to terminate with 50 ohms). The 10 ft. cable will cause a ~ 15 ns delay. Connect the TAC output to the PHA input, and switch the inhibit/out switch to "out" so that the TAC output is generated regardless of the SCA window. You should see the coincidence peak at about 15 ns. Then check in Labview to see that this GTT count rate is the same as the original GT count rate. Replace the cabling to the original connections.

Make Sure the GTR SCA Window is Set Correctly Disconnect the gate pulse from the GATE input of the START circuitry, and flip the associated switch to ANTI-coincidence. This effectively disables the GATE input on the START circuitry. No need to worry, we just checked to see that it works fine (see above). Now we want to set the SCA window to select TAC pulses initiated by simultaneous receptions of photons at the transmission and reflection detectors. We have already said (above) that we expect TAC pulses of about 3 volts amplitude. But of course we really don't expect photons to split in two and register simultaneously in the transmission and reflection detectors! So how are we going to check the SCA window? Here's the trick. Keep the transmission detector cable connected to the START input, but reroute the gate (idler) photon fiber coupler to the transmission detector by switching the fiber cable connections at the fiber connector manifold on the optical table. Now the gate photon will go to the transmission detector, and the reflected photon will go, as before, to the reflection detector. If the SPDC source is working at all, we would expect coincident gate and reflection photons. Check it out! Connect the TAC output to the PHA input, and use Maestro to make sure the SCE window is correctly set to measure these simulated GTR coincidences. Then use Labview to verify that the simulated GTR coincidences are counted. When you're finished with this procedure, replace the connections to their original configuration.

Measure $g^{(2)}(0)$ A typical measurement consists of 60 counting periods of 10 seconds each - a total of 10 minutes. Use your own judgment. You may want to make several

attempts at this measurement. It may be useful to make simultaneous measurements of count rates and the TAC spectrum from the GTR TAC/SCA module.

By now you are probably an expert on the system, and you may want to think about one of two options for continuing your work: (1) observing single-photon interference, or (2) performing a control experiment for your $g^{(2)}(0)$ measurement.

OPTION (1): Observing single-photon interference

You have now conclusively observed that a single photon goes one way, not both, at a beam splitter. It is now fascinating to perform the complementary experiment, in which you send photons one at a time through a Mach-Zehnder interferometer and observe that the count rate at the output is a function of the path length difference between the two interferometer arms. In other words, a single photon explores both paths of the interferometer! The combination of this experiment with the anticoincidence experiment encapsulates the “strangeness” of quantum phenomena.

In our apparatus, two beam-displacing prisms (BDP) and an 810 nm half-wave plate form a polarization interferometer that can be inserted in signal photon path. The first BDP encountered by a signal photon deflects horizontally polarized photons (denoted with a double-arrowed line in the plane of Fig. 6-6) so that they emerge from the prism at a spatially separated position from the vertically polarized photons (solid dot in Fig. 6-6). Next the 810 nm half-wave plate, whose optic axis is oriented at 45° from the vertical, converts the horizontally polarized photons to vertically polarized photons, and converts vertically polarized photons to horizontally polarized photons. As a result, the second BDP brings the two polarized beams back together again. The beams are now colinear, but cannot interfere because they are orthogonally polarized. The second 810 nm half-wave plate, if oriented with its optic axis at 22.5° from the vertical, will rotate the polarization of both beams by 45° . The polarizing beam-splitter (PBS) in the signal photon path will now select the vertical (horizontal) components of both beams and allow them to interfere on the reflect (transmit) detector. To observe interference fringes, the second BDP is rotated about a vertical axis, thus slightly changing the path length difference between the arms of the interferometer. This rotation is accomplished with a motorized actuator in the second BDP mount.

To obtain optimal interference fringes, the polarization (horizontal vs. vertical) of the signal photon must be completely unknown, even in principle, so that the signal photon takes both paths through the interferometer. Because the signal and idler photons are entangled in polarization, the idler photon carries information about the signal photon polarization (H vs. V) unless steps are taken to eliminate that information. One such step is to measure the idler photon polarization in the diagonal basis. Thus an 810 nm half-wave plate in the idler photon path should have its optic axis rotated to 22.5° from vertical; then an incoming diagonally (antidiagonally) polarized photon has its polarization rotated to vertical (horizontal) before it hits the polarizing beam splitter. Thus the detection of a photon by the gate (G) detector indicates that the idler photon was originally anti-diagonally polarized. This provides no information on the idler photon's

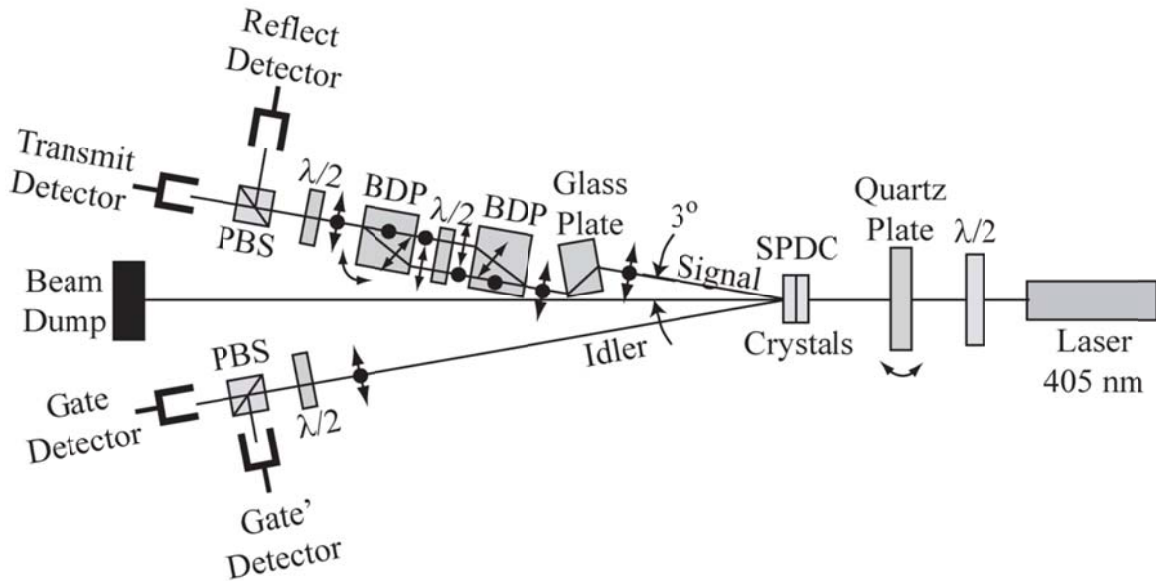


Fig. 6-6. Top view of the experimental setup for generating single photon interference fringes and demonstrating the principles of a quantum eraser. The quartz plate can be rotated about a vertical axis to zero the phase ϕ in the QM state for the entangled photon pairs. SPDC = spontaneous parametric down-conversion. BDP = beam-displacing prism. The second beam-displacing prism (BDP) in the signal path can be rotated about a vertical axis to generate interference fringes. PBS = polarizing beam splitter.

polarization in the horizontal/vertical basis, and thus does not reveal whether the *signal* photon is horizontally or vertically polarized. Therefore, both both paths through the interferometer will be explored. For this orientation of the idler half-wave plate, fringes will be observed in the records of the GT and GR or G'T coincidence count rates as the second BDP in the signal path is rotated.

The glass plate in the signal photon path introduces a displacement of the photons that compensates for the displacement introduced by the polarization interferometer. The net zero displacement allows the polarizing beam splitter and detectors to remain in the same positions they would occupy if the experimental setup is used without the interferometer.

To observe single-photon interference fringes, carefully insert the necessary elements (see below) into the signal and idler paths, using Figure 6-6 and the existing magnetic bases as your guides. Make every effort not to bump the elements as you handle them, and to settle them into their magnetic bases smoothly and gently. You may wish to begin with the half-wave plates, since these elements have the least sensitive alignment. If you bump knobs or other pieces of the interferometer, in particular, you and your instructor will likely spend significant time realigning the elements and finding the new equal-path-length position on the BDP actuator.

Insert in the idler path: idler half-wave plate, idler PBS.

Insert in the signal path: signal half-wave plate, interferometer, glass plate.

Use the LabVIEW program “Actuator Mover with 6 NIM Inputs” to collect coincidence counts as you rotate the second BDP. As of January 15, 2015, single-photon interference fringes can be found between actuator positions of 3.0mm and 3.4mm. Consult your instructor for any updates to this information.

OPTION (2): Performing a $g^{(2)}(0)$ control experiment

You can see the need for a good control - we are trying to measure zero convincingly! The FPGA module should be the best data acquisition hardware for measuring $g^{(2)}(0)$ for a classical light source, but it may have some problems, as you will see below. Robert Kealhofer and Chris Gage (both HMC '13) have written guides for the use of the FPGA module, and these guides are available in the lab and on the course Sakai site. It would also be prudent to measure $g^{(2)}(0)$ for our single-photon source using the FPGA module and compare the results with those obtained with the NIM electronics. Kaew Tinyanont and Yantao Wu, in an Optics Lab tech report in spring 2014, attempted this comparison, and their results suggest that the FPGA timing windows may be miscalibrated.