

# QIE - Quantum Interference & Entanglement

## Signature Sheet

Student's Name \_\_\_\_\_ Partner's Name \_\_\_\_\_

### Before the Lab

Before using the apparatus in this experiment, you must complete training in the safe use of lasers detailed on the [Laser Safety Training](#). This includes readings, watching a video, taking a Laser Quiz, and filling out a Laser Training Certificate form. You must turn in the completed forms into the 111 Lab Staff before you start the experiment.

### Pre-Lab Discussion Questions

It is your responsibility to discuss this lab with an instructor before your first day of your scheduled lab period. This signed sheet must be included as the first page of your report. Without it you will lose grade points. You should be prepared to discuss at least the following before you come to lab:

1. What is the significance of an observation of a violation of a Bell inequality? What does it mean for the validity of Quantum Mechanics as well as for the character of possible alternative theories?
2. In the experiment you will use half-wave plates to control the Bell state as well as the basis in which it is measured. A half-wave plate is a slice of birefringent crystal that allows the perpendicular polarization of incident light with respect to the preferred axis (the optical axis) to pass through unchanged, but delays by 180 degrees as compared to the parallel polarization with respect to the optical axis. Given this, (1) what is the output polarization of light passing through a half-wave plate whose optical axis forms an angle  $\theta$  with the polarization axes of the incident light? (2) If you wish to change horizontally polarized light into light that is in an equal superposition of horizontal and vertical polarizations – that is, polarized at 45 degrees relative to the horizontal – at what angle should you set your wave plate? Explain how this effect can be used to change the measurement basis.
3. In the experiment, we have the following optical elements, listed in the order the photon will encounter them: a half-wave plate, a horizontal polarizer, and a detector.

- (a) We will analyze the number of coincident photons  $N(\alpha, \beta)$  as a function of the orientation of the measurement basis where the angles  $\alpha$  and  $\beta$  specify the orientation of the measurement basis for each photon. To understand the nature of the Bell-states it is useful to study the expected measurement results in the following bases  $(0^\circ, 0^\circ)$ ,  $(0^\circ, 90^\circ)$ ,  $(45^\circ, 45^\circ)$  and  $(90^\circ, 90^\circ)$ . Note that these are not the actual waveplate settings. (See previous question.)

Assuming a **perfect Bell state and zero phase difference between the vertical and horizontal downconverted photons**, i.e.  $|\psi\rangle = (1/\sqrt{2})(|hh\rangle + |vv\rangle)$ , what rate of coincidences do we expect to see for each basis setting, if we know the system is generating 1000 downconverted photon pairs per second?

Show the instructor code to calculate the expectation values for arbitrary angles, it will be useful later to analyse the data on the fly.

Of course, the real use of these measurements is when our downconverted photons are not in the ideal entangled case. Let's look at two important cases of this.

- (b) Suppose that our first half waveplate is slightly off from its correct value, and as a result **our down-converted pairs are more likely to be horizontally polarized than vertically**

**polarized.** For example, instead of being in the state  $|\psi\rangle = (1/\sqrt{2})(|hh\rangle + |vv\rangle)$ , they are now in the state  $|\psi\rangle = (\sqrt{3}/2)|hh\rangle + (1/2)|vv\rangle$ . How do we expect each of these measurements to change?

- (c) Now suppose that our setup is producing **vertically and horizontally downconverted photons in equal numbers again, but they are no longer entangled**-that is, it is emitting light that is a 50-50 mix of horizontally polarized photon pairs and vertically polarized photon pairs. What would you now expect from each of these measurements? This is what we could observe if our experiment followed a local hidden variable theory.
- (d) Now suppose that our setup is producing a **pure entangled (Bell) state again, but that there is a phase difference between the horizontal and vertical components of the state**. Now what do we expect from each of these measurements? This is why we have an angled birefringent plate in the 405nm beam path, to compensate for the space between the two BBO crystals.
- (e) Discuss which measurement setting(s) will be most helpful to get insights into the quality of the Bell state. Which one tells you most about the quantum nature, i.e. that you are dealing really with a superposition between  $|hh\rangle$  and  $|vv\rangle$ .
4. Pairs of photons are created via a down-conversion process. Discuss briefly what happens and what path you expect the photon pairs to take. What does this mean for how one has to align the detectors with respect to the violet pump beam? Pay attention both to the horizontal and the vertical position.
5. Our coincidence counting works in the following manner: each time a photon hits one detector, the FPGA waits 5 ns afterwards to see if a photon hits any other detector. Of course, there are some background counts on each detector due to ambient light, and every now and then two of those counts will come close enough together to register a “false” coincidence. Determine the expected rate of these false coincidences in terms of the rate of counts on each detector and the coincidence time window. If each detector gets 50,000 background counts per second, what rate of background coincidences do you expect for a 5-ns coincidence window? How does this scale if you double the amount of background light (which doubles the count rates on each detector)?
6. What is the statistical error in the number of counts on each detector? How about the statistical error in the number of coincidences?
7. Suppose that as you start to perform your experiment, two of your friends come crashing into the room to see what you are doing, one through each wall (like the Kool-Aid Man) at a speed of  $.9999c$  (in opposite directions) when they enter. Unfazed, you explain the experiment and how it works, but once you start to describe how the wave function collapses when measured, one of your friends cuts you off. “That’s all fine,” he says, “but there’s just one thing: I saw you running those photon pairs as I arrived,” - he’s quite a talented fellow - “and the photons going to detector A were always about 19 ns delayed from the ones going to detector B. So it was the measurement of those photons that collapsed the entangled state, right?”  
Before you can answer, your other friend jumps in: “You mean the ones going to detector B were delayed, right?” she asks, puzzled. “That’s what I saw.”  
How do you reconcile what your friends saw? What implications does this have for how entanglement works?
8. Explain which practices you will follow while setting up and disassembling the optics as well as with the fibers ([Optics Tutorial](#)). In particular, show the instructor how you will plug a fiber into or unplug from a connector.

Staff Signature \_\_\_\_\_ Date \_\_\_\_\_

Completed before the first day of lab? (Circle one) Yes / No

### Mid-Lab Discussion Questions

By day 4 of this lab, you should have successfully aligned the laser and produced a well tuned Bell state.

1. Report the phase adjust angle you found to maximize the coincidence counts at any polarization.
2. Report the calculated contrast for coincidence counts as you fix the angle at half-wave plate A and vary the angle at half-wave plate B. Discuss with the instructor if you get a value close to 1.
3. Together with question 2, discuss with an instructor what calculated  $\theta$  and  $\phi$  you get from your preliminary data. Are they close to your expectation?
4. Which pairs of half-wave plate angles are you planning to use for your measurement of  $S$ ? Why are these the best values to use for your entangled state? Make sure you have math to back you up.

Staff Signature \_\_\_\_\_ Date \_\_\_\_\_

Completed by day 4 of lab? (Circle one) Yes / No

### Checkpoint Signatures

1. Laser Goggle Safety Check

Staff Signature \_\_\_\_\_

2. Blue-Violet Beam Path

Staff Signature \_\_\_\_\_

3. Infrared Beam Path

Staff Signature \_\_\_\_\_

4. Angle

Staff Signature \_\_\_\_\_

5. Arbitrary Offset

Staff Signature \_\_\_\_\_

6. Bell-State Characterization

Staff Signature \_\_\_\_\_