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 incident light whose polarization is perpendicular to some preferred axis (the optical axis) to pass through unchanged but delays by 180 degrees as compared to light whose polarization is algined with the optical axis. Given this, what is the output polarization of light passing through a half-wave plate whose optical axis forms an angle θ with the polarization axes of the incident light? 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 waveplate? 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(α,β) as a function of the orientation of the measurement basis where the angles α and β 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 $(0°, 0°), (0°, 90°), (45°, 45°)and(90°, 90°)$. 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.

   (b) 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. 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 5050 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.

4. Our coincidence counting works in the following manner: each time a photon hits one detector, the FPGA waits 5ns 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)?

5. What is the statistical error in the number of counts on each detector? How about the statistical error in the number of coincidences?

6. 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?

7. 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 2.24.23

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

Mid-Lab Discussion Questions

By day 3 or 4 of this lab, you should have successfully aligned the laser and produced a well tuned Bell state.

1. Record and report your half-wave plate calibrations.
2. Create a graph that shows the purity of your Bell state and show it to a GSI for a signature. Also, show your quantified bell state (coefficients C_1,C_2, and phase ϕ).

3. Which pairs of half-wave plate angles will you 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.

4. Please measure the output power of the laser diode after the optical Isolator and show and tell the professor or GSI. Document this number.

Staff Signature WLH Date 3/2/23

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

Checkpoint Signatures

1. Violet Beam Path

   Staff Signature ______________________

2. Angle

   Staff Signature ______________________

3. Infrared Beam Path

   Staff Signature ______________________

4. Arbitrary Offset

   Staff Signature ______________________

5. Bell-State Characterization

   Staff Signature ______________________

QIE

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March 2023

Abstract

This lab investigates quantum entanglement and interference and attempts to violate Bell's inequality. The experimental setup includes a source of entangled photons and detectors to measure the photons' coincidence. The results of the experiment provide evidence for validating quantum mechanics against local hidden variable theories.

1 Introduction

1.1 Bell's Theorem and the CHSH Inequality

In this lab report, we will be exploring the concept of entanglement and interference by trying to violate Bell's theorem and the CHSH inequality. Bell's theorem provides a way of testing whether or not quantum mechanics is a complete theory or whether there are hidden variables that govern the behavior of entangled particles. The CHSH inequality, which stands for Clauser-Horne-Shimony-Holt inequality, is a simple but powerful test for violations of local realism. Successful experimental verification could prove against hidden variable theory and provide new insights into the nature of entanglement and interference.

Many researchers have attempted to verify these concepts experimentally, and some have been successful in doing so. We will concentrate on investigating the polarization of entangled photon pairs. Here is the polarization correlations[1]:

$$E(\alpha, \beta) = \frac{N(\alpha, \beta) + N(\alpha_\perp, \beta_\perp) - N(\alpha, \beta_\perp) - N(\alpha_\perp, \beta)}{N(\alpha, \beta) + N(\alpha_\perp, \beta_\perp) + N(\alpha, \beta_\perp) + N(\alpha_\perp, \beta)} \tag{1}$$

where $N(\alpha, \beta)$, is the number of coincidence of photon pairs polarized at α and β. We need 4 measurements of N to get one E.

$$S = E(a, b) - E(a, b') + E(a', b) + E(a', b') \tag{2}$$

where a, a', b, b' are four different polarizer angles that we set. We need 4 measurements of E thus 16 measurements of N to get S. Local hidden variable theory and quantum theory both yield $|S| \leq 2$. We aim to find certain angle a, a', b, b' and expect to show that $|S| > 2$ as predicted in quantum mechanics.

2 Experimental Procedures

2.1 Laser Beam generating entangled states through BBO

For this experiment, We used a 120-mW, 405-nm violet diode laser to generate photons. In Figure 1, we tested the stability of the laser right after the optical isolator and set the current of the laser to be 100.01mA. We wanted to have as many photons as possible while the laser didn't experience lags.

After the optical isolator, the pumping laser pass through a half-wave plate, two turning mirror, another half-wave plate, a phase adjuster, and two BBO crystals in order. The two

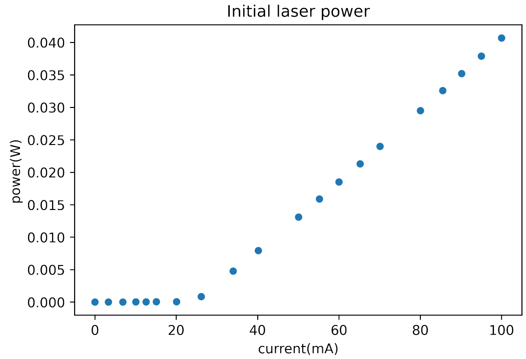


Figure 1: Initial laser power

BBO crystals are nonlinear beta barium borate (β-BaB2O4) and optical axes are rotated 90 from each other. Each BBO crystal converts only photons of a single polarization. Here is how the BBOs downconvert 405nm pump photons to a pair of 810 nm entangled "signal" and "idler" photons:

$$|\psi_{pump}\rangle = cos\theta_l \, |V\rangle_p + e^{i\phi_l} sin\theta_l \, |H\rangle_p \tag{3}$$

$$|\psi_{DC}\rangle = cos\theta_l \, |H\rangle_s |H\rangle_i + e^{i\phi} sin\theta \, |V\rangle_s |V\rangle_i \tag{4}$$

$$\phi = \phi_l + \Delta \tag{5}$$

Δ is caused by the birefringence and dispersion within the BBOs and the relative phase between them. Thus ϕ is the total relative phase. A half-wave plate is usually made of a birefringent device that rotate the polarization of light by 2θ, where θ is the angle from the optical axis of the plate. We used the two half-wave plates to rotate the polarization of light so that diffraction of light was minimized before reaching the BBOs. We then used the phase adjuster to set θ_l to counter against Δ. The beam should come out through the center of BBOs when aligned.[2]

2.2 Infrared beam path alignment

We aligned a infrared beam path to make sure that 810nm beams would hit the the center of each detector. We did the alignment in a reverse direction of the 810nm beam path. After removing the long pass filter on each detector, we connected the back side of each detector with a portable infrared laser. Each infrared beam came through the front of each detector, hit the center of the corresponding beam splitter cube, passed through the center of the corresponding half-wave plate, and eventually focused at the center of the BBOs. The beam splitter cube allows horizontally polarized light to pass and reflects vertically polarized light out at 90°.

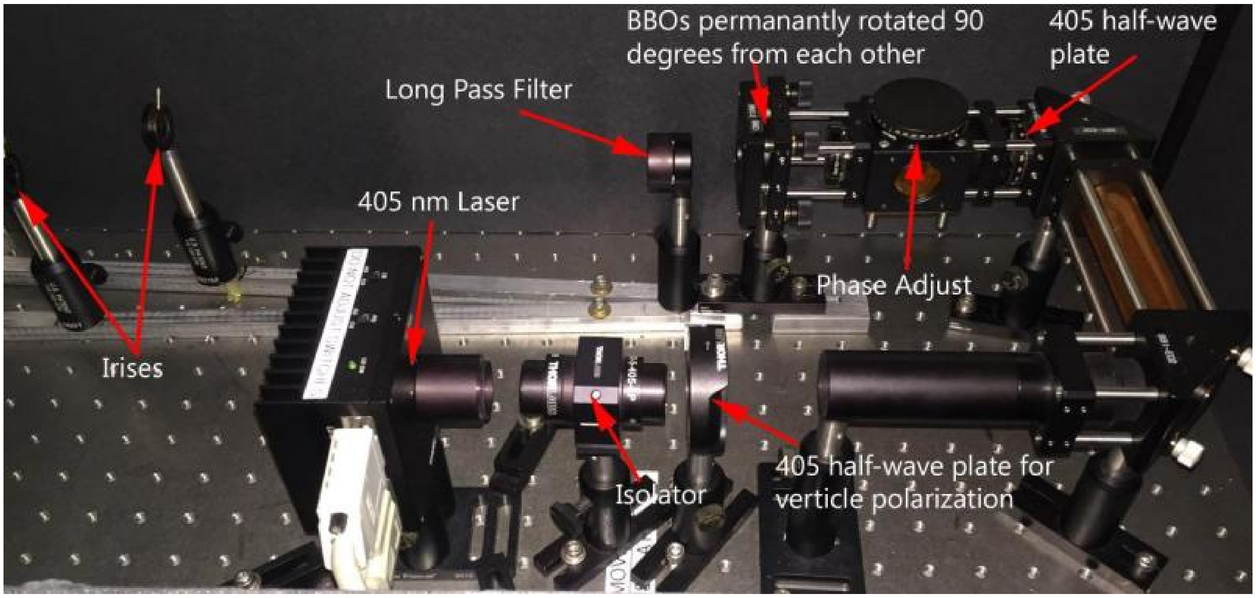


Figure 2: Photo of violet beam path

2.3 Detection

When light hit the detection part, a fiber coupler (FC) len focuses the light into an optical fiber. Light travel through the optical fiber and reach an avalanche photodiode (APD), which converts single photons into 1 V electronic pulses. The electronic signals are sent to a field-programmable gate array (FPGA) to calculate the coincidence rate. A coincidence is the arrival of two photons at different detectors within 5 ns. Photon counts for each detector and coincidence counts for each pair of detectors are recorded in a specially designed LabView program on the computer.

We adjusted the detection Arm Angle and found the optimal angles that gave the maximum coincidence were 46° for arm A and 21° for arm B

Table 1: this is a caption of a table

Names	Age	height	weight(lbs)
carter	20	6’8	90
Abby	32	5’4	100
Max	25	6’1	100

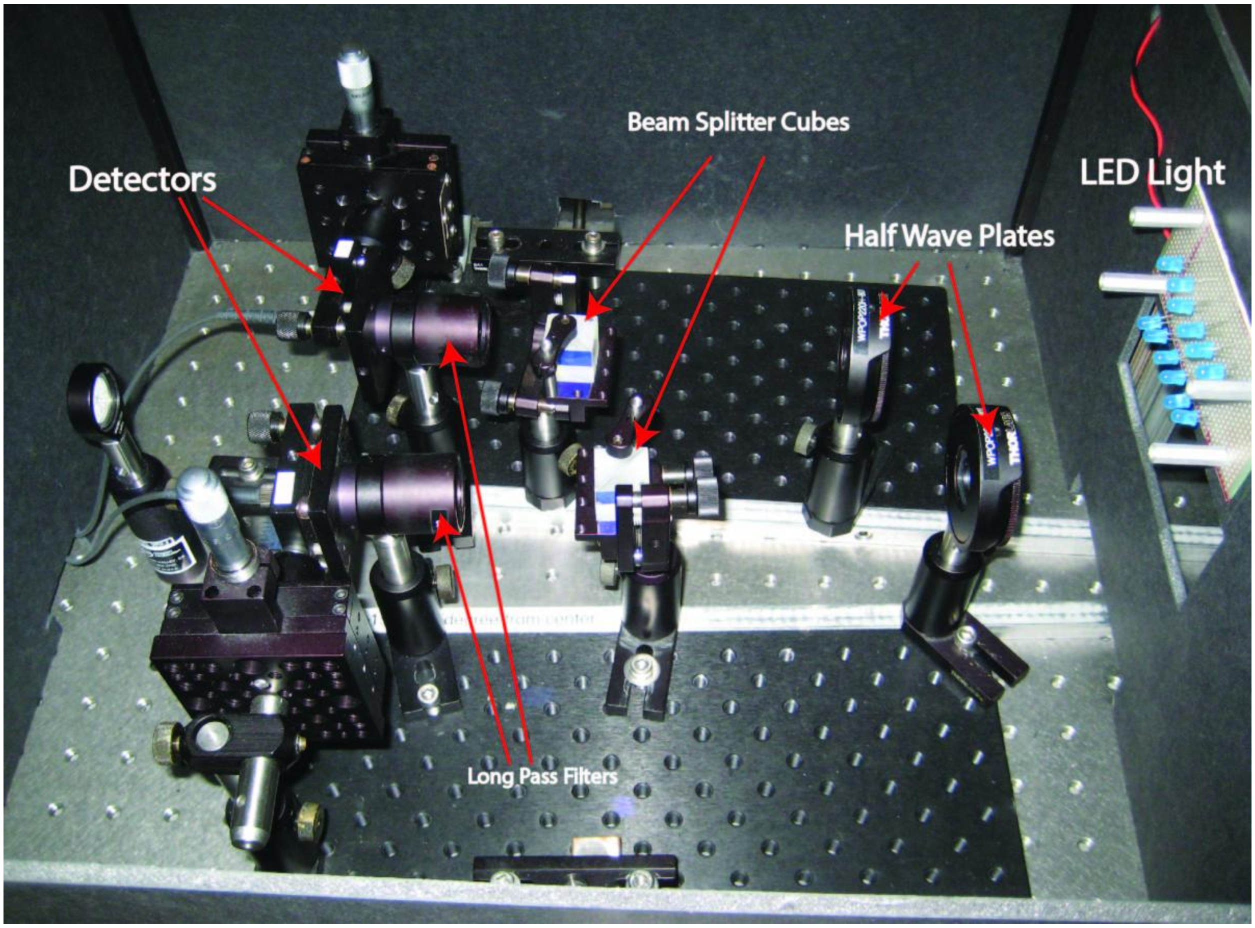
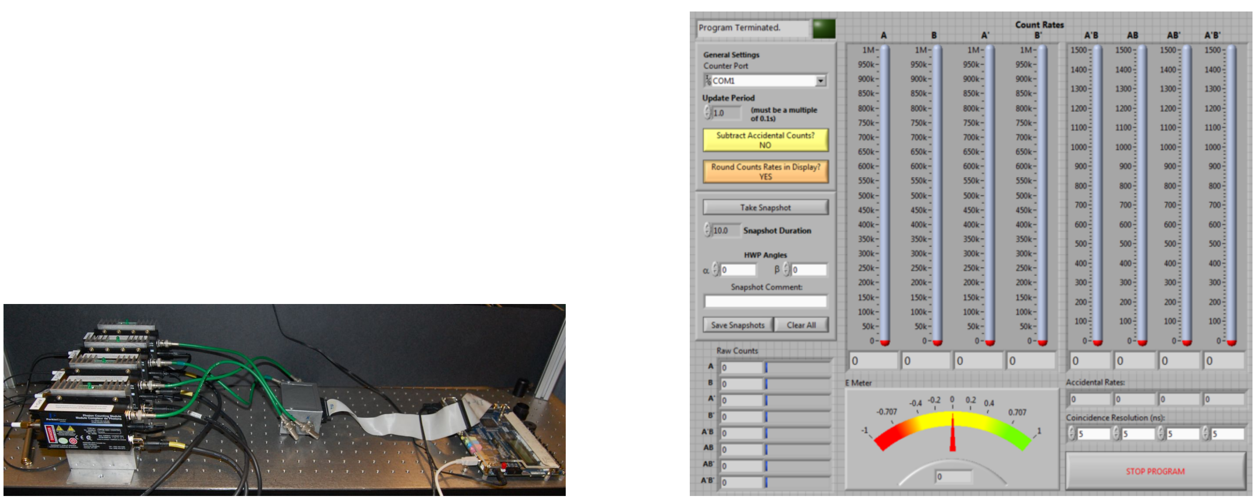


Figure 3: Photo of infrared beam path



(a) APDs (left) send data to FPGA card (right)

(b) Front panel of QIE Counter.vi

Figure 4: Detection parts

3 Results and Analysis

Using equation 1 and 2 and combining with our experimental data, we got S = 2.109 which was a violation of CHSH Inequality.

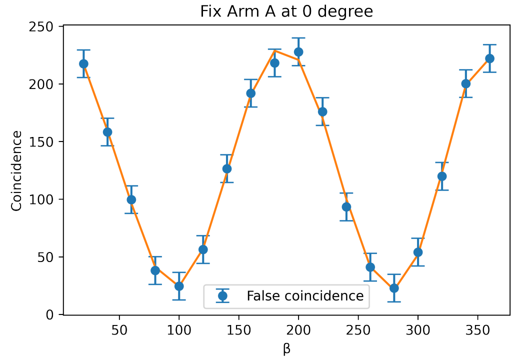


Figure 5: Coincidence count when fixing Arm A at 0 degree

Table 2: 16 coincidence measurement of N

	$\beta = -22.5°$	$\beta = 22.5°$	$\beta = 67.5°$	$\beta = 112.5°$
$\alpha = -45°$	182	15.65	151.1	226
$\alpha = 0°$	162.7	173.08	10.03	148.6
$\alpha = 45°$	10.04	202	181	16.38
$\alpha = 90°$	110.13	41.2	215	183.4

4 Conclusion

In conclusion, the experiment successfully demonstrated the principles of quantum entanglement and interference. The creation and measurement of entangled photons showed the non-locality and correlation of quantum systems.

References

(1) Lukishova, S. G.; Stroud, C. R.; Bissell, L.; Zimmerman, B.; Knox, W. H. Teaching experiments on photon quantum mechanics. *Frontiers in Optics* **2008**, SThD3.

(2) Dehlinger, D.; Mitchell, M. Entangled photons, nonlocality, and Bell inequalities in the undergraduate laboratory. *American Journal of Physics* **2002**, *70*, 903–910.