QIE

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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. $\alpha_\perp = \alpha + 90°$. $\beta_\perp = \beta + 90°$. 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. As shown 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.

The violet beam path is shown in Figure 2. An optical isolator was used to protect laser diodes from backscattered light. After the optical isolator, the pump laser passed through a

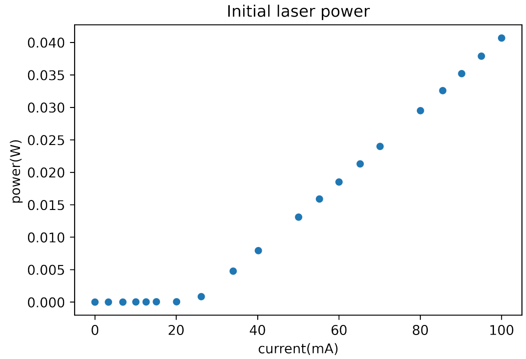


Figure 1: Initial laser power

half-wave plate, two turning mirror, another half-wave plate, a phase adjuster, and two BBO crystals in order. The two BBO crystals are nonlinear beta barium borate (β-BaB2O4) and their optical axes are permanently 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:

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

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

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

θ_l is the angle of polarization before reaching the BBO crystals. Δ is caused by the birefringence and dispersion within the BBOs and the relative phase between them. Thus ϕ is the total relative phase of the two polarization components. A half-wave plate is made of a birefringent device that rotates 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 ϕ_l to counter against Δ. The beam came 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 the 810nm photons would hit the the center of each detector. We did the alignment in a reverse direction of the 810nm beam path. The infrared beam path is shown in Figure 3. 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°.

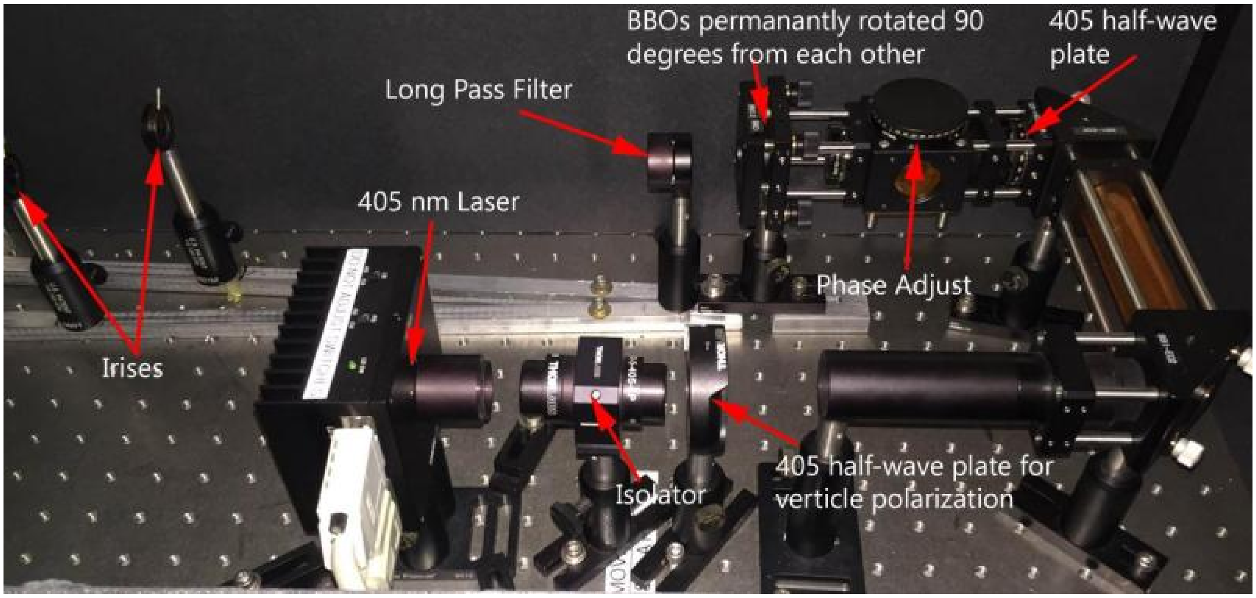


Figure 2: Photo of violet beam path

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(Figure 4a). 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(Figure 4b) 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

We use the halfwave plates here to set the basis V and H for measuring polarizations of signal and idler photons:

$$|V_\alpha\rangle = cos\alpha|V\rangle - sin\alpha|H\rangle \tag{6}$$

$$|H_\alpha\rangle = sin\alpha|V\rangle + cos\alpha|H\rangle \tag{7}$$

$|V_\alpha\rangle$ and $|H_\alpha\rangle$ are states with polarization rotated by α from the vertical and horizontal respectively. With two waveplates, the probability of coincidence detection for V_α and V_β is

$$P_{VV}(\alpha, \beta) = |\langle V_\alpha|_s \langle V_\beta|_i|\psi_{DC}\rangle|^2 \tag{8}$$

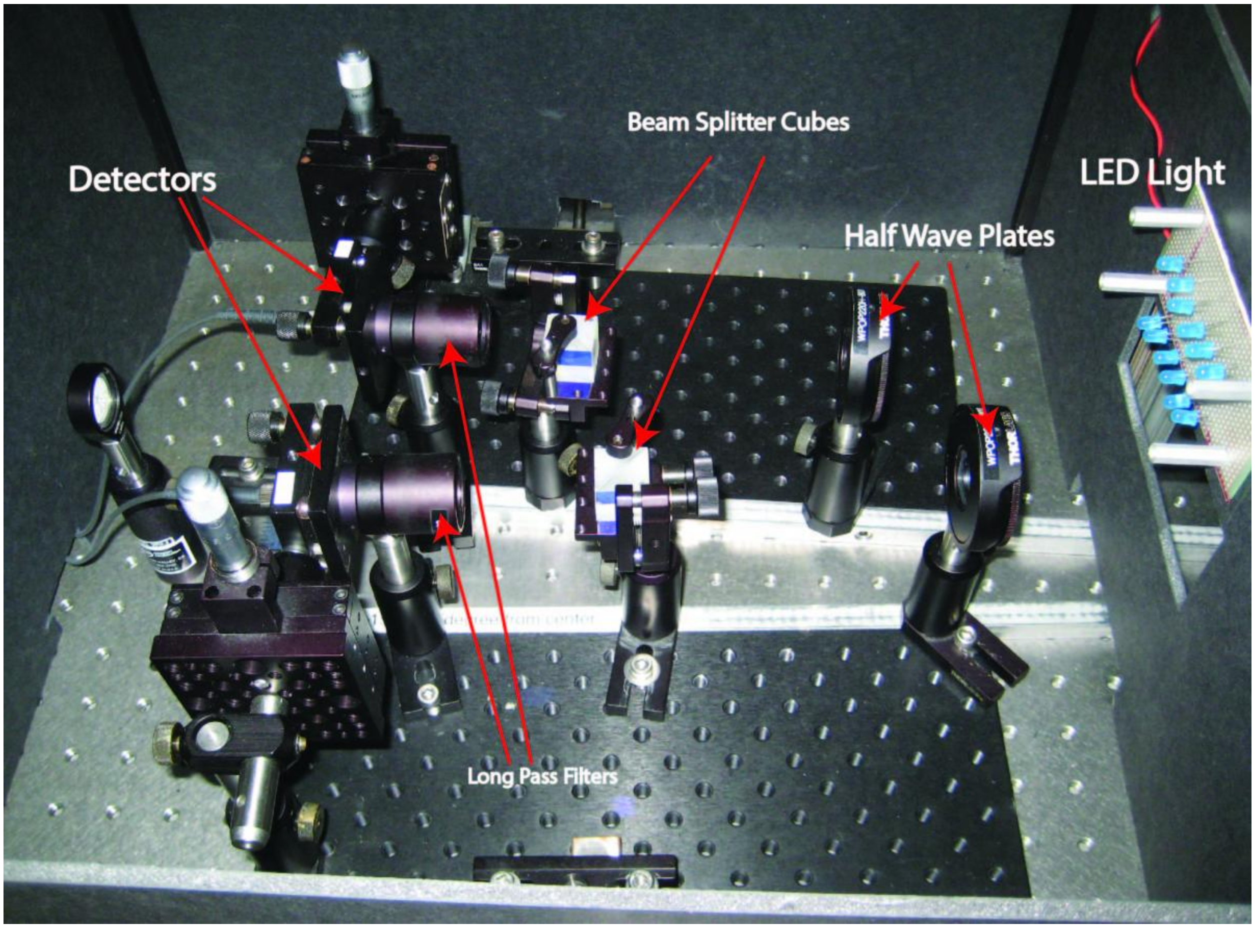


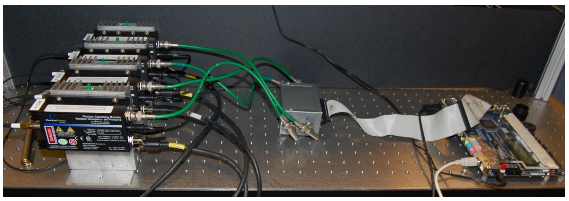
Figure 3: Photo of infrared beam path

$$P_{VV}(\alpha,\beta) = sin^2\alpha\ sin^2\beta\ cos^2\theta_l + cos^2\alpha\ cos^2\beta\ sin^2\theta_l + \frac{1}{4}\sin 2\alpha\ sin2\beta\ sin2\theta_l\ cos\phi_m \quad (9)$$

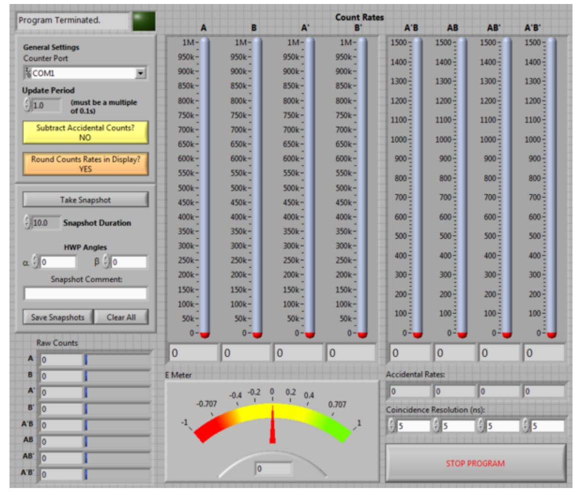
$cos\phi_m$ is the average of $cos\phi$ since the detectors collect photons over a finite solid angle and wavelength range. The number of coincidence is then

$$N(\alpha,\beta) = A(sin^2\alpha\ sin^2\beta\ cos^2\theta_l + cos^2\alpha\ cos^2\beta\ sin^2\theta_l + \frac{1}{4}\sin 2\alpha\ sin2\beta\ sin2\theta_l\ cos\phi_m) + C \quad (10)$$

where A is the total number of entangled pairs produced, and C is an offset to account for imperfections in the polarizers and alignment of the crystals.



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

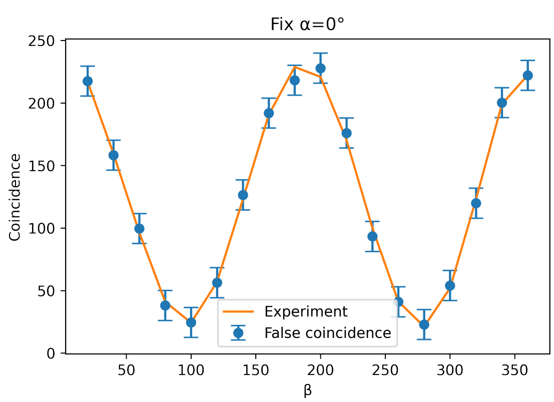


(b) Front panel of QIE Counter.vi

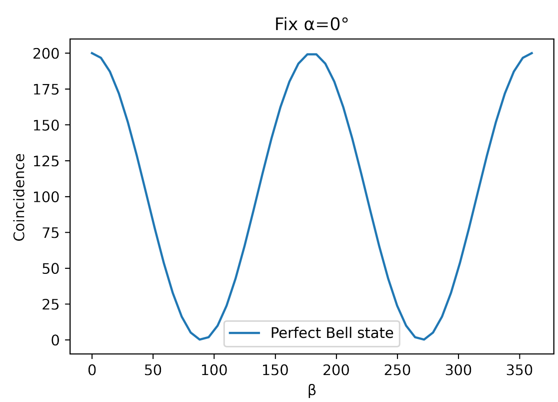
Figure 4: Detection parts

3 Results and Analysis

We measured the polarization of photon pairs in different α and β basis and then compared with the theoretical Bell state. We tried to test the purity of our state by fixing α and varying β. Using Equation 10, we plotted perfect Bell states(ie. $\theta_l = 45^\circ$ and $\phi = 0^\circ$). By fitting our measurements, we plotted the experimental states which showed high similarities with expectations in Figure 5 & 6. The experimental states presented slight phase shift from the perfect Bell state due to imperfections of the waveplates.



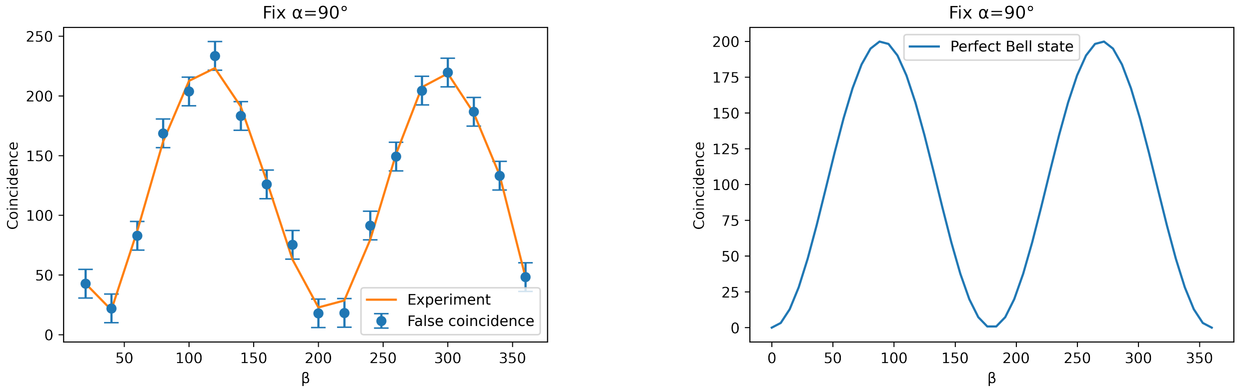
(a) Experiment



(b) Theory

Figure 5: Coincidence count when fixing α at 0°

A set of coincidence measurements is shown in Table 1. Plugging experimental data of N into equation 1 & 2, we got S $= 2.11 \pm 0.02 > 2$, which was a violation of CHSH Inequality.



(a) Experiment

(b) Theory

Figure 6: Coincidence count when fixing α at 90°

Table 1: 16 coincidence measurement N

	$\beta = -22.5°$	$\beta = 22.5°$	$\beta = 67.5°$	$\beta = 112.5°$
$\alpha = -45°$	182	15.65	151.1	206
$\alpha = 0°$	180.7	173.08	10.03	148.6
$\alpha = 45°$	10.04	202	181	16.38
$\alpha = 90°$	100.13	41.2	215	183.4

4 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. A more detailed analysis in coincidence counting could be beneficial for understanding the mysteries of quantum mechanics.

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.