Simulating Quantum Physics and Quantum Computer Science Phenomena using a Virtual Quantum Optics Laboratory (VQOL)

Parth Shroff, Adam Spiegel, Stephan Jabs
The University of Texas at Austin

Supervisors: Brian R La Cour, Noah Davis

Introduction

- Our goal was to design, conduct, and analyze quantum-optics experiments in VQOL.
- Experiments include Quantum State Tomography, Mach-Zehnder Interferometer/Wheeler's Delayed Choice, Quantum Key Distribution, and Violation of the Bell-CHSH Inequality.
- In most experiments, the main questions in addition to experiment-specific inquiries pertained to the relationship between quantum and classical behavior.
- What set of parameters worked best to obtain accurate probabilities/fidelities?, How was the quality of the procedure? What does the experiment suggest about the quantum phenomena?

What is VQOL?

- VQOL is a virtual simulation of a quantum optics laboratory with implementations of different linear optical devices.
- VQOL presents a realistic model of quantum optics as classical optics with real, stochastic vacuum fields in the form of the Zero-Point Field excitations.
- VQOL interprets measurement outcomes as deterministic threshold-crossing events.
- VQOL post-select results to consider only valid measurement outcomes.

QKD Image

Basic depiction of a QKD setup in VQOL with half-wave plates, neutral density filters, polarizing beam splitters and single-photon detectors

Materials and Methods

- VQOL is implemented in Python 3 (Tkinter, NumPy, SciPy, and PIL dependencies).
- For most experiments, a Bash or Python script would generate the setup in VQOL, vary parameters for different optical devices, and log results.
- In the Mach-Zehnder and Wheeler's Delayed Choice experiment, the interferometer was set up so that an interference pattern could be obtained by varying the phase delay.
- For both QST schemes, the goal was to prepare and verify an arbitrary quantum state. Once the detector counts were converted into sample means, the density matrix of the quantum state was reconstructed.
- In single-qubit QST, we measured the prepared state in either the H/V, D/A, or R/L basis by calculating the sample mean in each of the four Pauli matrices.
- For multi-qubit QST, two photons were being measured and thus, 16 total sample mean measurements were obtained when measuring in different combinations of bases.

Results

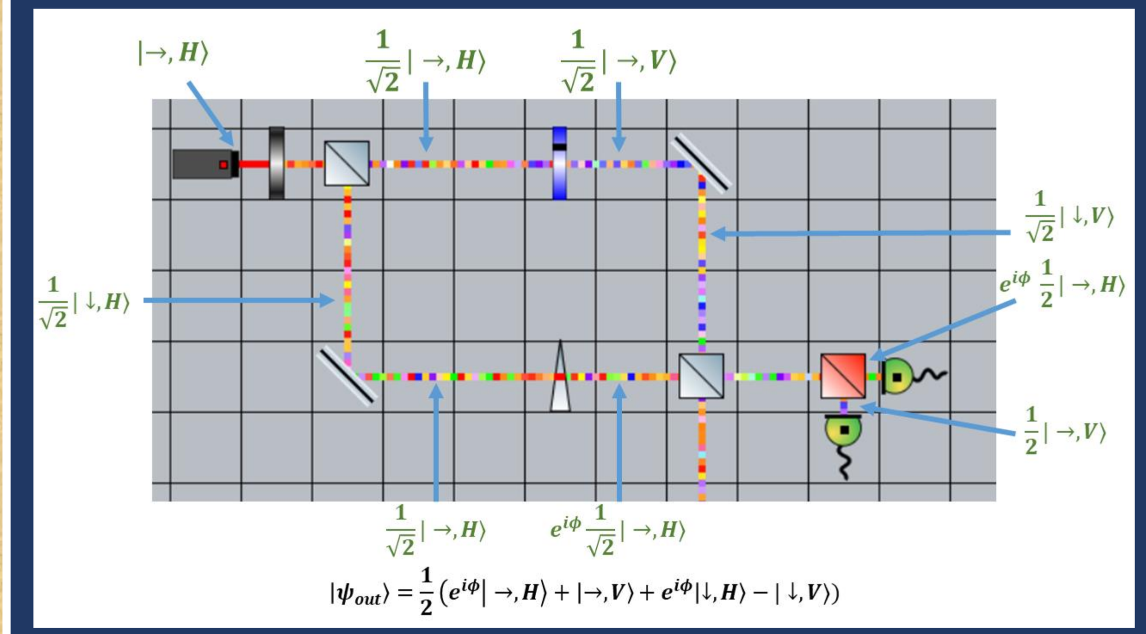

Figure 1. Wheeler's Delayed Choice Experiment where the Mach-Zehnder Interferometer has been modified with the addition of the X gate in order to extract information about which beam the light came from after a detection event

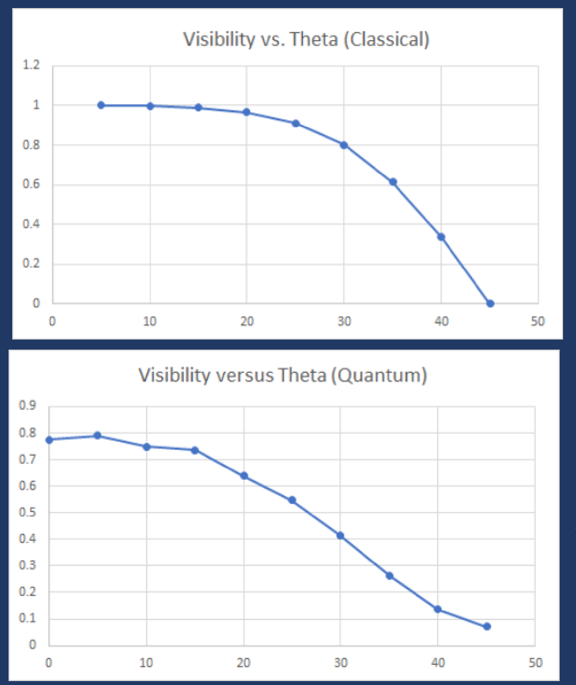

Figure 2. Visibility vs Fast Axis Angle

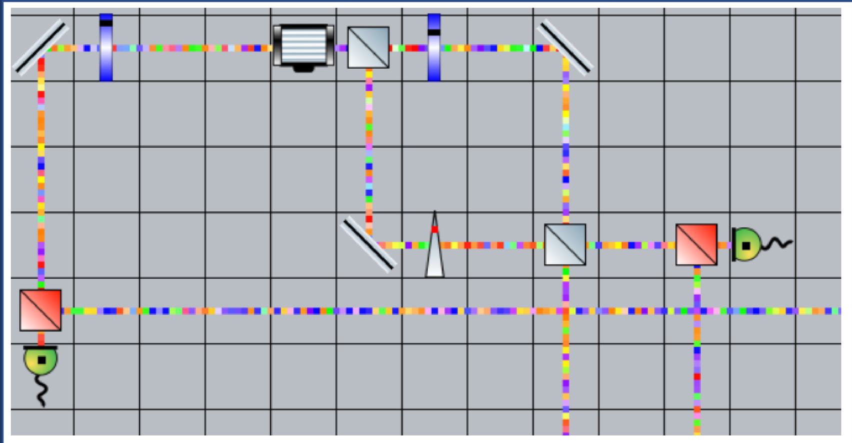

Figure 3. Recovering the interference pattern by remotely "erasing" the which-way information without altering the Mach-Zehnder Interferometer

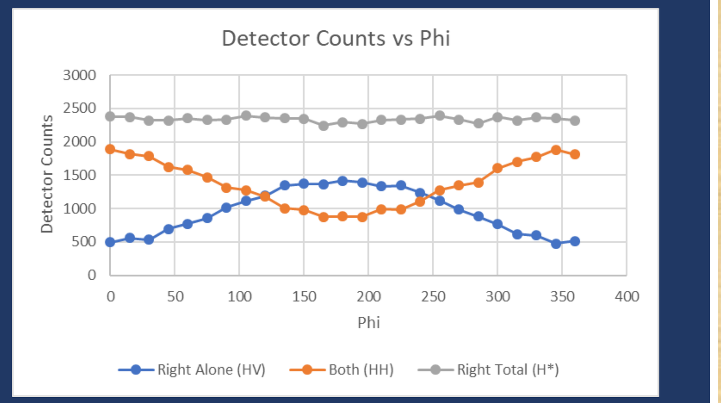

Figure 4. Counts vs Phi (with "eraser")

$$\frac{1}{2}\left(\begin{bmatrix}1&0\\0&1\end{bmatrix}+\begin{bmatrix}0&1\\1&0\end{bmatrix}M_X+\begin{bmatrix}0&-i\\i&0\end{bmatrix}M_Y+\begin{bmatrix}1&0\\0&-1\end{bmatrix}M_Z\right)=\frac{1}{2}\begin{bmatrix}1+M_Z & M_X-M_Y i\\M_X+M_Y i & 1-M_Z\end{bmatrix}$$

Figure 5. Formula to reconstruct the density matrix (Single-Qubit QST)

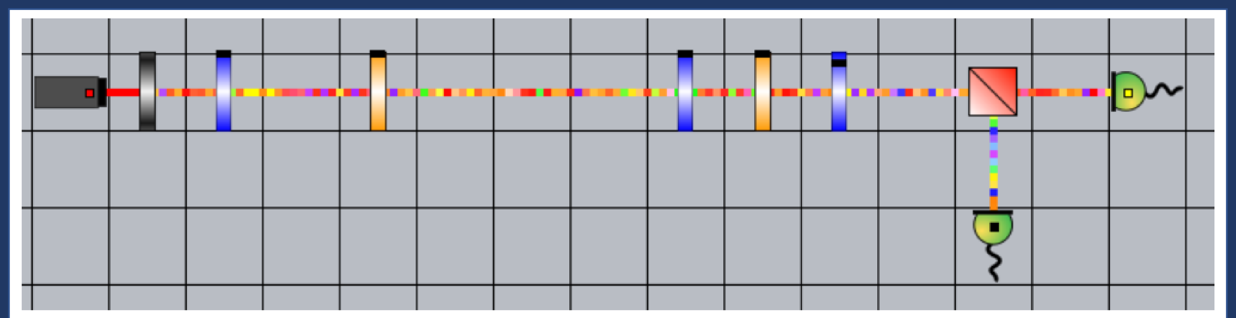

Figure 6. Single Qubit QST Setup (RL Basis)

	XX	XY	XZ	XI	YX	YY	YZ	YI	ZX	ZY	ZZ	ZI	IX	IY	IZ	II
|00>	1	1	1	1	1	1	1	-1	1	1	1	1	1	-1	1	1
|01>	-1	-1	-1	-1	-1	-1	-1	1	-1	-1	-1	1	1	-1	1	1
|10>	-1	-1	-1	1	-1	-1	-1	-1	-1	-1	-1	-1	-1	1	-1	1
|11>	1	1	1	-1	1	1	1	1	1	1	1	-1	-1	1	-1	1

Table 1. Two-Qubit QST Table of Eigenvalues

R	PDC	Fidelity	Eigenvalues				Valid
1	0.005	0.979981	0.980341	0.011139	0.008723	0.022074	Yes
1	0.01	0.971132	0.971672	0.029569	0.007639	0.006398	Yes
1	0.05	0.970264	0.971006	0.001215	0.012527	0.017681	Yes
1	0.1	0.984615	0.98556	0.023902	0.009717	0.019178	Yes

Table 2. Two-Qubit QST results for R = 1 (Squeezing Parameter in SPDC) and varying Probability of Dark Count (PDC)

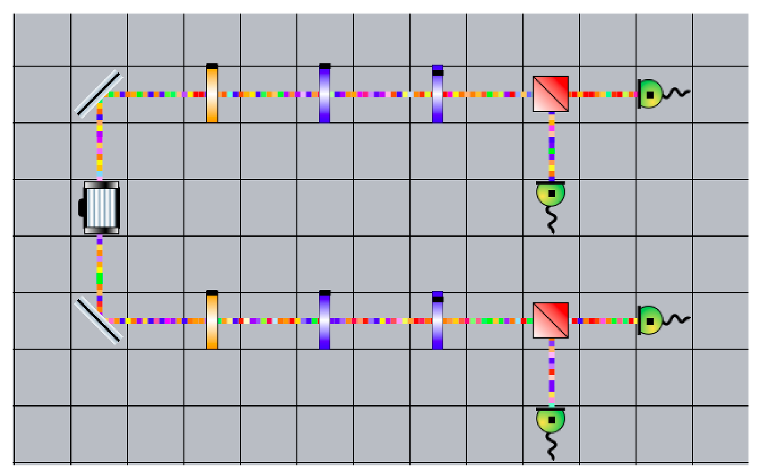

Figure 8. Two-Qubit QST Setup (YY measurable)

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0.49      , 0      , 0.02      , 0.48
0         , 0      , 0         , 0
0.02      , 0      , 0         , 0
0.48      , 0      , 0         , 0.49
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Figure 9. Two-Qubit QST Experimental Density Matrix R = 1, VarPhi = 0

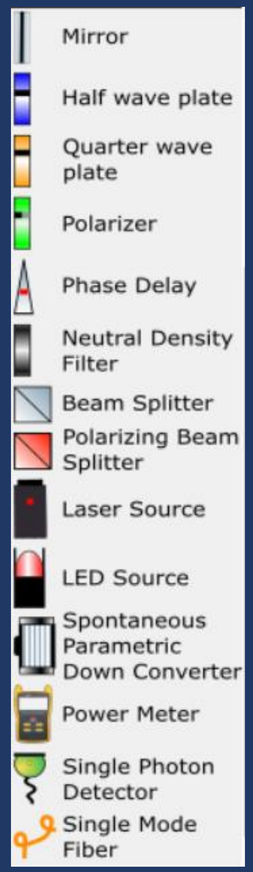

Figure 10. Reference Key

Conclusions & Future Work

- The addition of the half-wave plate with varying fast axis values (Fig. 1) lower the observed visibility as theta approached 45°.
- Thus, when no information is extracted from the experimental setup, light destructively interferes and behaves as a wave. When information is obtained, light behaves as a particle. (Fig. 2).
- An atomic-level setup of the Mach-Zehnder Interferometer should be implemented to compare their efficiencies (swapping the spatial and polarization mode) (Manning et al. 539).
- This information can be erased (Fig. 3 & 4) and the interference pattern reappears.
- In both QST schemes, the results from VQOL were stable (valid eigenvalues and density matrices) (Fig. 6, 8 Table 2).

References

La Cour Brian R. *Summer 2020 Quantum Optics Program*, ARL:UT, 9 August 2020

Manning, A. G., et al. "Wheeler's Delayed-Choice Gedanken Experiment with a Single Atom." Nature Physics, vol. 11, no. 7, 2015, pp. 539–542., doi:10.1038/nphys3343.