Analysis of a Single Photon, 2-Qubit Spatial Mode System: Implementing A Linear Polarization-Based Approach to Bell State Entanglement and Grover's Algorithm

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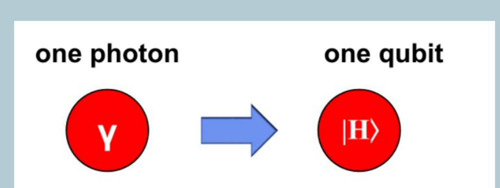
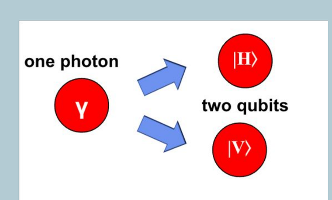
Introduction

Quantum communications stands at the forefront of providing enhanced data security by exploiting the laws of quantum mechanics. A major challenge in the field has been the costly process of manufacturing a substantial number of qubits – the building blocks of quantum information protocols. Our research introduces an innovative approach to reproduce standard quantum algorithms within a single photon, significantly bolstering the scalability of quantum communication systems. Additionally, by reducing the number of photons required for such protocols, our project paves the way for a more cost-effective production of qubits.



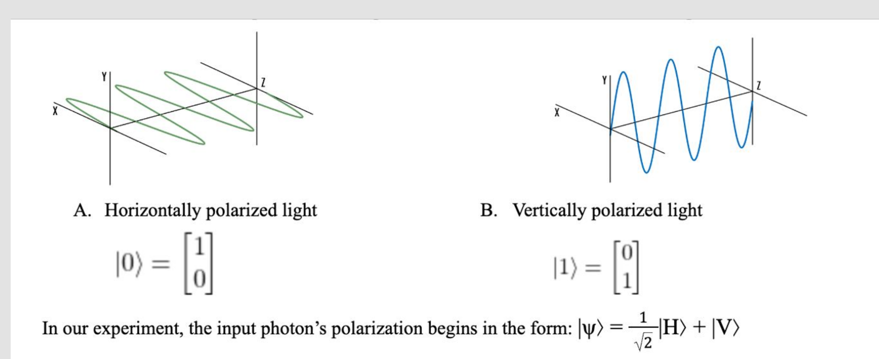


Our project aims to modify the standard one qubit per photon ratio, effectively enabling multiple qubits to be encoded within a single photon.

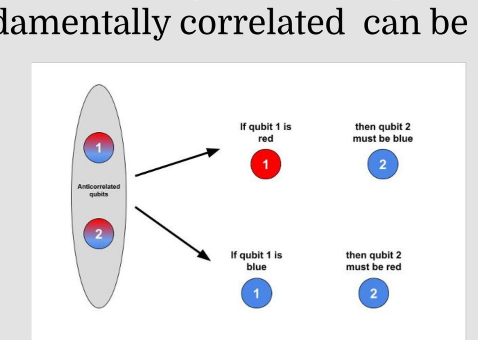
Satellite communication → Quantum internet → Information transfer

Background

For a single photon, the 2-qubit system is represented as the photon's two spatial modes A and B. Quantum information is stored in the qubits' polarization, which can either be horizontal, vertical, or a superposition of both



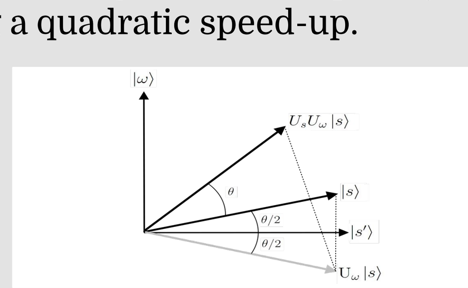
Quantum entanglement is a phenomenon where two qubits are fundamentally correlated can be described as a single system



$$|\psi\rangle_{in} = \frac{1}{\sqrt{2}}(|H\rangle_A + |V\rangle_A) \otimes |V\rangle_B$$

$$|\psi\rangle_{out} = \frac{1}{\sqrt{2}}(|H\rangle_A|V\rangle_B + |V\rangle_A|H\rangle_B)$$

Grover's algorithm is a quantum search algorithm that quickly finds items in an unsorted list, providing a quadratic speed-up.



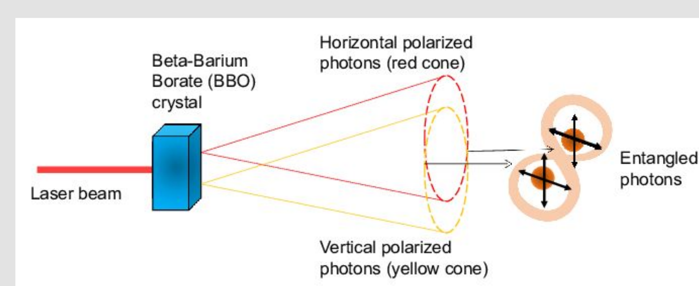
Materials

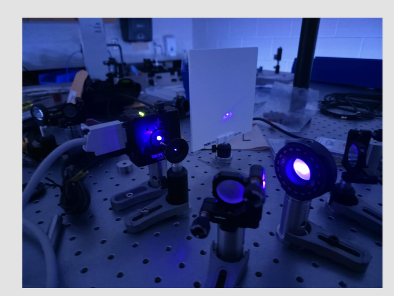
Our experiment was performed using a variety of software tools for simulation, as well as hardware for the physical implementation. We used a Python-based, linear optical quantum computing library called Perceval for photon detection analysis. For entanglement correlations and Grover's algorithm, we used another Python-based quantum computing library called Qiskit. Finally, our hardware implementation was inspired from the ThorLabs Quantum Optics Educational Kit.

Qiskit PERCEVAL THORLABS

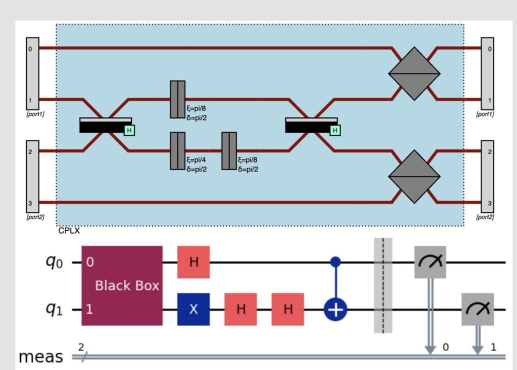
Methodology

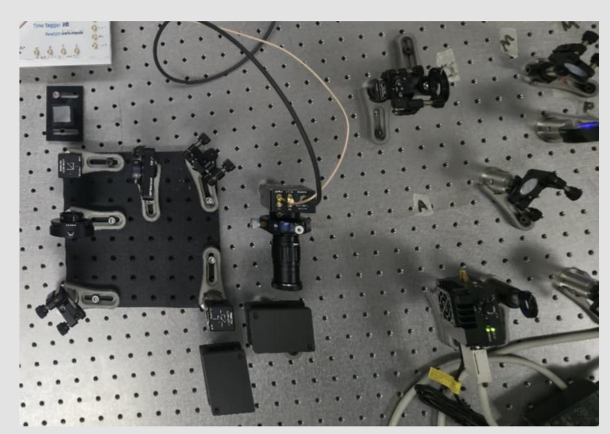
Bell State Entanglement





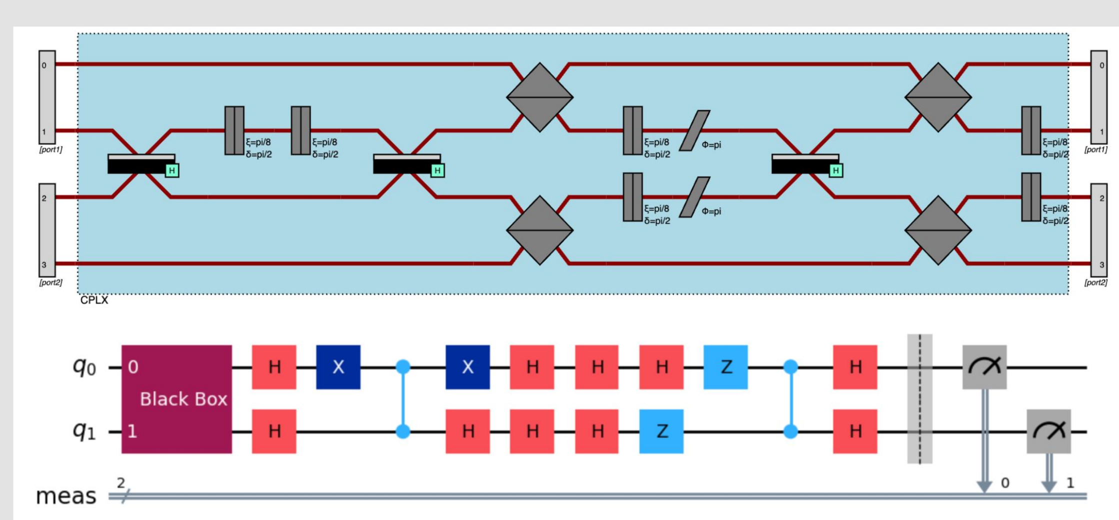
We generate our single photon source using a standard nonlinear BBO crystal, isolating one half of the entangled pair for our experiment.





Software and hardware implementations of entanglement in the third bell state. First, polarization is encoded in the spatial modes using waveplates, then the HOM effect is measured at the PBS and detectors.

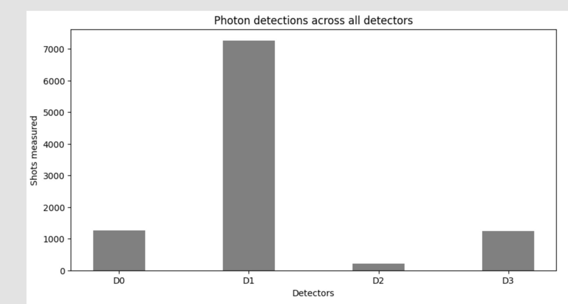
Grover's Algorithm

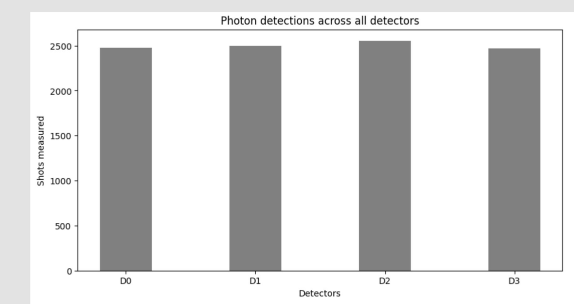


Software implementation of Grover's algorithm in Perceval *(top)* and equivalently in Qiskit *(bottom)*.

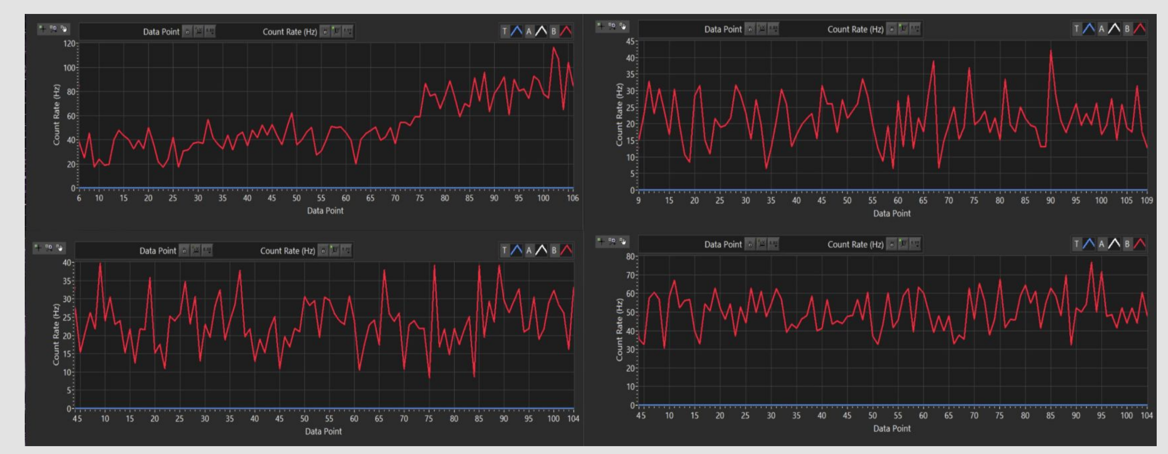
Results

Bell State Entanglement

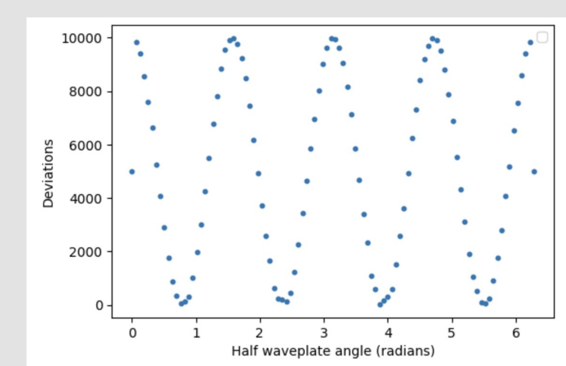


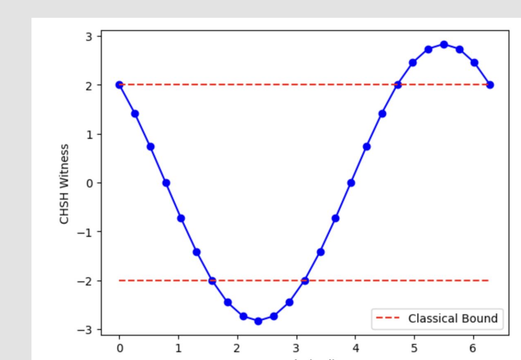


Left: Photon detections in Perceval when the circuit is imbalanced (without second HWP). ***Right***: Photon detections when the circuit is balanced.



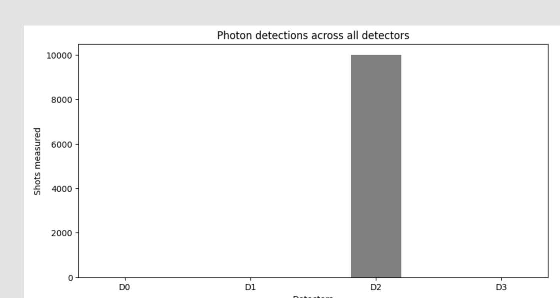
Photon detections at each of the four detectors in our ThorLabs setup.

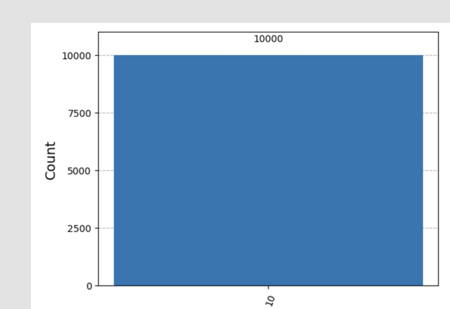




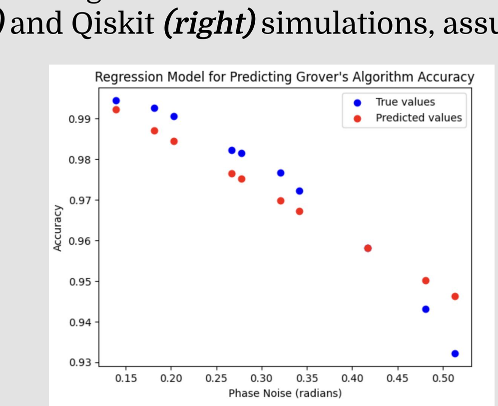
Left: Photon detections in Perceval as the QWP is rotated in 45° increments. ***Right***: Violation of Clauser-Horne-Shimony-Holt inequality in Qiskit.

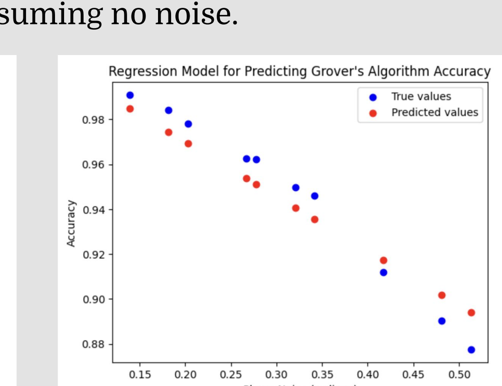
Grover's Algorithm





Grover's algorithm finds the marked state 100% of the time in both Perceval ***(left)*** and Qiskit ***(right)*** simulations, assuming no noise.





Accuracy of Grover's algorithm under the presence of variant phase noise in both Perceval ***(left)*** and Qiskit ***(right)*** simulations.

Discussion

- **What we investigated**
  - Can we implement Bell State entanglement and Grover's algorithm using a single photon, 2-qubit system encoded in polarization and spatial modes?
- **Why it's interesting**
  - Scalable, fault-tolerant photonic quantum computing
  - Encoding qubits within single-photon spatial modes
- **What we accomplished**
  - Demonstrated Hong-Ou-Mandel effect at each detector
  - Demonstrated Bell state violation of CHSH inequality
  - Achieved 98.8% accuracy for Grover's with noise

Limitations: While photons were distributed evenly across all four detectors, we no longer detected entanglement between our single photon source and the other half of its entangled pair. This could indicate that our count rate was proliferated by external interference, rather than the single photon.

Future Work/Applications

- **Encoding more information**
  - Qudit encoding of different degrees of freedom such as spin and momentum
- **Improving scalability further**
  - Extending the schematic to systems of > 2 modes using diffractive optical elements (DOE) opening a realm of possibilities

Enhancement of algorithms such as the E91 cryptography protocol or quantum teleportation. → Integration into large scale quantum devices, such as NASA's Quantum Communication's Project → Overall reduction in manufacturing costs for building multi-qubit photonic quantum computing systems.

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Acknowledgements

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