Analyzing Variations within the Delayed-Choice Quantum Eraser Experiment

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Research Objective

This experiment is conducted in two approaches:

Theoretical Simulation

- Theorize a mathematical model of a two-state system to predict the experimental result
- Develop a simulation to test the mathematical model of the quantum eraser

Experimental

- Build a coincidence detection system
- Test the coincidence counter using real time data from Geiger counters, pulse generators, and eventually photo detectors.

Background

Wave-Particle Duality

- Young's double slit experiment demonstrates light acting as both a particle and a wave.
- Light through two slits creates interference patterns, evidencing wave-like properties.
- The "Which Way? Information" problem: Determining photon paths disrupts the wave behavior, eliminating the interference pattern.

Quantum Entanglement and Non-Locality

- Principle of locality: No influence can travel faster than light, according to relativity.
- Quantum entanglement challenges this, suggesting non-local interactions where entangled particles affect each other instantaneously over distances.
- **Temporal Entanglement:** Correlation established at a specific moment in time.
- **Non-Temporal Entanglement:** Correlation persists regardless of the time frame, defying classical constraints of speed and time.

Coincidence Detector

Theory

- Coincidence detectors are critical in quantum experiments for measuring and correlating events precisely.
- Operates by receiving signals from multiple detectors, registering events only when signals arrive simultaneously or within a very short window.
- Essential for discerning entangled particles and ensuring they are part of the same quantum phenomena.

```python
import RPi.GPIO as GPIO
import time

# Setup GPIO
GPIO.setmode(GPIO.BCM)
GPIO_PIN1 = 17  # Replace with your first GPIO pin number
GPIO_PIN2 = 18  # Replace with your second GPIO pin number
GPIO.setup(GPIO_PIN1, GPIO.IN, pull_up_down=GPIO.PUD_UP)  # Assuming act
GPIO.setup(GPIO_PIN2, GPIO.IN, pull_up_down=GPIO.PUD_UP)  # Assuming act

coincidence_count = 0

try:
    while True:
        input1 = GPIO.input(GPIO_PIN1)
        input2 = GPIO.input(GPIO_PIN2)

        if input1 == 0 and input2 == 0:
            coincidence_count += 1
            print("Coincidence detected! Total count:", coincidence_coun

        time.sleep(0.0001)  # Adjust polling rate as necessary

finally:
    GPIO.cleanup()
```

Figure 1. Code Snippet

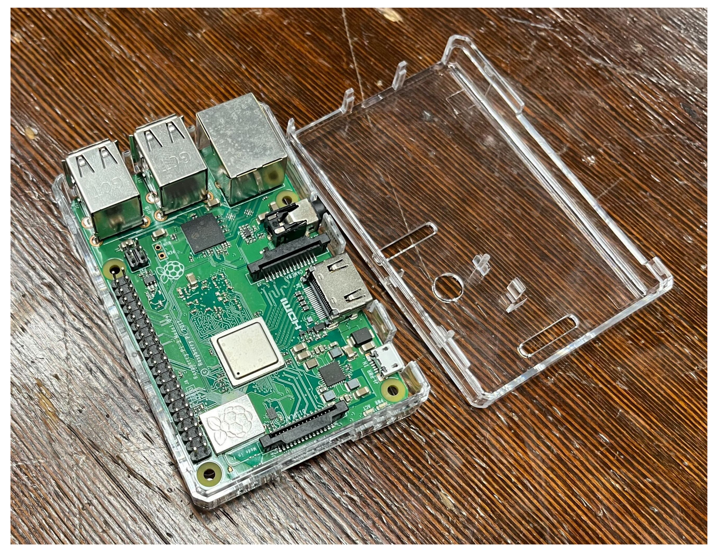

Figure 2. Raspberry Pi

In Our Experiment

- Initial setup used a Programmable System on Chip, later switched to a Raspberry Pi for enhanced capabilities.
- Display upgraded from an LCD screen to a monitor for better visualization of coincidence counts over typical 10-second runtimes.
- Used two Geiger counters as input channels to test the coincidence detection system.
- Developed Python code to simultaneously compare input channels and detect coincidences.
- A coincidence is recorded when both channels detect a signal at the exact same moment.

Theoretical Mathematical Method

A BBO nonlinear crystal splits incoming photons into two entangled photons with lower energy and momentum. Each is either horizontally or vertically polarized. This process is known as the Spontaneous Parametric Down-conversion. Without polarizes, the system is in the state

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|x\rangle_R\,|y\rangle_L + |y\rangle_R\,|x\rangle_L) \tag{1}$$

The state of left photon is not known, therefore one should expect **wave distribution**. By putting a left and right circular polarizer in front of slit 1 and 2, the state of system becomes

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\psi\rangle_1 + |\psi\rangle_2) \tag{2}$$

where

$$|\psi\rangle_1 = \frac{1}{\sqrt{2}}(|x\rangle_{s1}\,|y\rangle_L + |y\rangle_{s1}\,|x\rangle_L)$$
$$|\psi\rangle_2 = \frac{1}{\sqrt{2}}(|x\rangle_{s2}\,|y\rangle_L + |y\rangle_{s2}\,|x\rangle_L)$$

In this case, the which-way information is obtained after measurement on left photon by detector 1. Due to the **collapse** of the quantum state, one should expect **particle distribution**. With a diagonal linear polarizer in front of detector 1, the which-way information is erased, therefore one should expect a recovery of **interference distribution**.

Theoretical Simulation Data

Without varying path distances
Scenario 1 (1 left and 1 right circular polarizer at D1; 1 diagonal polarizer at D2):

- When photon R reaches D4, the state of photon L is **obtained**.
- Quantum state information cannot be obtained by D3 due to the double slits.
- When photon L reaches double slits at D1, with the information of state obtained, the **which-way information is obtained**, generating a particle distribution in figure 2.

Scenario 2 (1 left and 1 right circular polarizer at D1; 1 diagonal polarizer at D2; 1 diagonal linear polarizer at D1):

- The which-way info is **erased** by the diagonal polarizer at D4.
- State of the two-photon system is unknown.
- Producing a wave distribution in figure 3.

With Varying path distances:
Scenario 3 (same as scenario 2 but path L is shorter than R):

- Photon L reaches D1 before D4, which-way information is not obtained until photon R reaches D4.
- Producing wave distribution
- When photon R reaches D4, which-way information is obtained.
- Changing from wave distribution to particle distribution in figure 4.
- **If such distribution is detected, no abnormality is found, otherwise, potential non-temporal entanglement is involved.**

If no change in any distribution above is detected, non-locality is potentially involved.

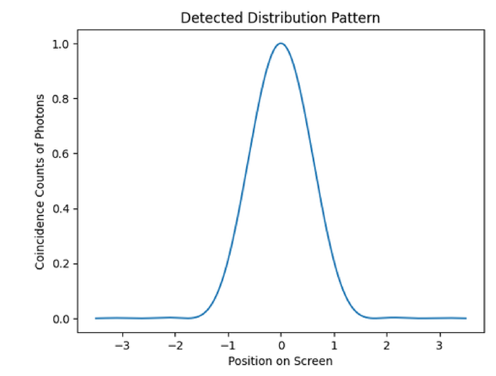

Figure 3. Particle Pattern

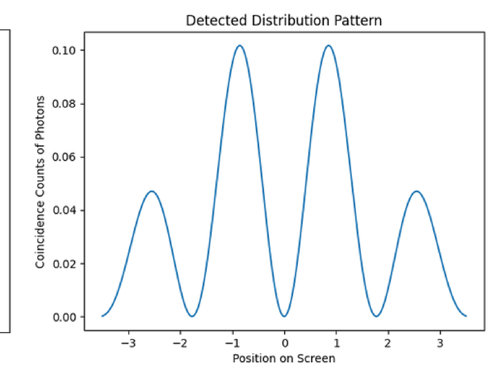

Figure 4. Wave Pattern

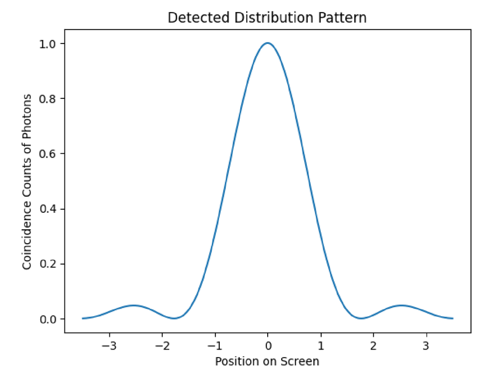

Figure 5. Quantum Eraser Pattern

Data

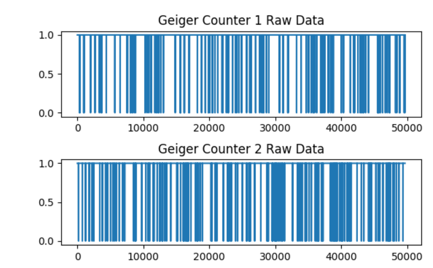

Figure 6. Geiger Counter Raw Data 10kHz

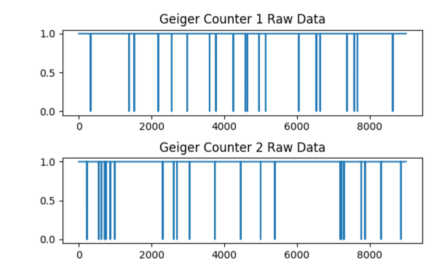

Figure 7. Geiger Counter Raw Data 1kHz

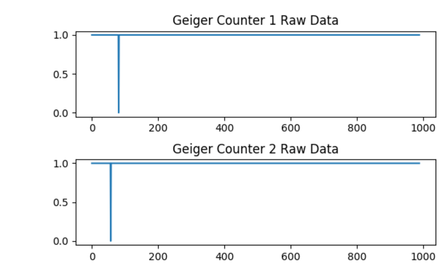

Figure 8. Geiger Counter Raw Data 100Hz

We would like to adjust the window of detection so more coincidences can be detected, our current window is too strict.

Future Plans

Extended Theoretical Exploration

Enhance understanding of **quantum mechanics fundamentals** such as entanglement, superposition, and wavefunction collapse. Focus on **Spontaneous Parametric Down-conversion (SPDC)** for generating entangled photons and explore its impact on measurement outcomes based on polarization.

Experimental Design

- **Setup Details:** Discuss calibration and specifics of lasers, BBO crystals, polarizers, and detectors.
- **Measurement Techniques:** Describe technologies for photon coincidence detection and interference pattern capture.
- **Parameter Variability:** Assess effects of changes in slit widths, distances, wavelengths, and screen distances.

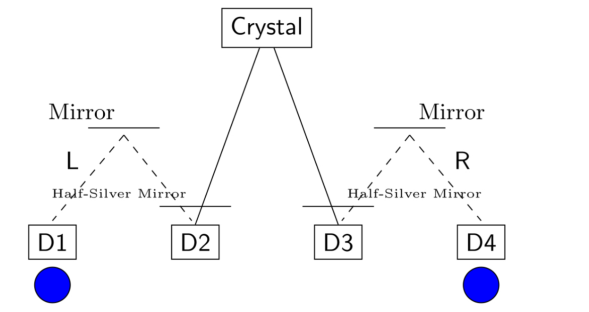

Figure 9. Theoretical Experiment Setup where blue circles represent potential polarisers.

Simulation Enhancements

Suggest improvements to simulation models:

- Incorporate complex quantum states and additional polarizers.
- Model effects of quantum noise and decoherence.
- Simulate realistic detector efficiency and error rates.

Advanced Data Analysis and Broader Implications

Discuss advanced data analysis techniques, including statistical analysis and machine learning, to interpret complex data patterns. Explore implications for **quantum computing**, **quantum cryptography**, and fundamental physics, highlighting how findings could influence quantum algorithms, secure communication, and theoretical understanding.

References

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