Photon Interference

Single Photon and Bi-Photon

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Outline

Wave-particle duality

- Light in the form of waves, in or out of phase, either constructively or destructively interfere with one another
- Incident discrete wave packets (photons) with sufficient energy may eject electrons
    - Photoelectric effect
- The fact that light can behave in either of these manners is referred to as Wave Particle Duality.

Outline

- The Single Photon Interference Experiment demonstrates that a photon may interfere with itself when it may reach a detector by means of either of 2 indistinguishable paths.
- Feynman provides three Quantum Mechanical Conditions by which interference may occur

3 Quantum Mechanical Conditions Interference

- The probability P of an outcome from a particle interacting with an apparatus is the square of the absolute value of its complex probability amplitude ϕ
  - $P = |\phi|^2$
- If the same outcome can occur in indistinguishable ways, the probability amplitude is the sum of probability amplitudes for each way separately:
  - $P = |\phi_1 + \phi_2|^2$
- If an experiment determines which way the outcome occurred, then the probability is the sum of each alternative
  - $P = P_1 + P_2 = |\phi_1|^2 + |\phi_2|^2$

Can it be explained classically?

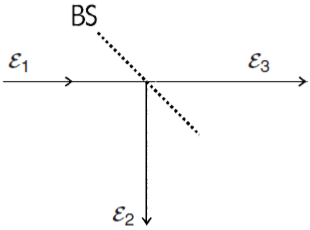

Figure: Beam splitting in the classical sense.

- ε_2 and ε_3 are the amplitude of the reflected and transmitted beams,
- r and t are the complex reflectance and transmittance of the beam-splitter

Can it be explained classically?

- $\varepsilon_2 = r\varepsilon_1$ and $\varepsilon_3 = t\varepsilon_1$
- Loss-less beam-splitters
  - $|\varepsilon_1|^2 = |\varepsilon_2|^2 + |\varepsilon_3|^2$
  - $|r|^2 + |t|^2 = 1$
- If treat the beam-splitter quantum mechanically (replace ε_i with annihilation operators $\hat{a}_i$)

$$\begin{pmatrix} \hat{a}_2 \\ \hat{a}_3 \end{pmatrix} = \begin{pmatrix} r\hat{a}_1 \\ t\hat{a}_1 . \end{pmatrix} \tag{1}$$

Can it be explained classically?

- Fails the commutation relationships
- $$[\hat{a}_2, \hat{a}_2^\dagger] = |r|^2[\hat{a}_1, \hat{a}_1^\dagger] = |r|^2$$
$$[\hat{a}_3, \hat{a}_3^\dagger] = |t|^2[\hat{a}_1, \hat{a}_1^\dagger] = |t|^2$$
$$[\hat{a}_2, \hat{a}_3^\dagger] = rt \neq 0$$

What went wrong!?

Correct Interpretation

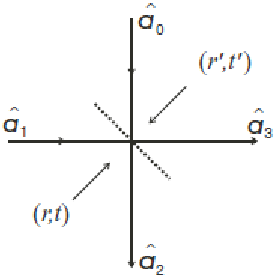

Figure: Beam splitting quantum-mechanically

- $$\begin{pmatrix} \hat{a}_2 \\ \hat{a}_3 \end{pmatrix} = \begin{pmatrix} r\hat{a}_1 + t'\hat{a}_0 \\ t\hat{a}_1 + r'\hat{a}_0 \end{pmatrix} \tag{2}$$

Mach-Zehnder interferometer

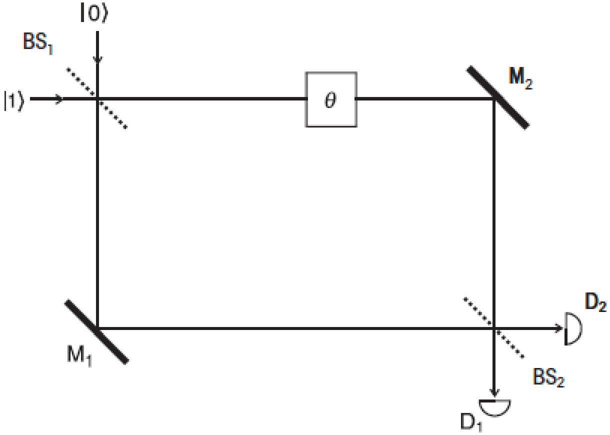

Figure: MZI. BS_1 and BS_2 are beam-splitters, θ is the phase difference, M_1 and M_2 are mirrors, and D_1 and D_2 are detectors.

Mach-Zehnder interferometer

- Consider the state $|0\rangle|1\rangle$ entering the MZI and interacting with the first beam splitter (BS_1)
- $$|0\rangle|1\rangle \rightarrow t|0\rangle|1\rangle + r|1\rangle|0\rangle.$$
- Once this reaches the second beam-splitter (BS_2) there will/might be a phase length θ_1 and θ_2

$$|0\rangle|1\rangle \rightarrow e^{i\theta_1}(r|0\rangle|1\rangle + t|1\rangle|0\rangle)$$
$$|1\rangle|0\rangle \rightarrow e^{i\theta_2}(t|0\rangle|1\rangle + r|1\rangle|0\rangle)$$

Mach-Zehnder interferometer

- the final state is given by,

$$t(e^{i\theta_1}(r|0\rangle|1\rangle + t|1\rangle|0\rangle)) + r(e^{i\theta_2}(t|0\rangle|1\rangle + r|1\rangle|0\rangle))$$

  or

$$rt(e^{i\theta_1} + e^{i\theta_2})|0\rangle|1\rangle + (tte^{i\theta_1} + rre^{i\theta_2})|1\rangle|0\rangle.$$

-

$$\begin{aligned} P_{10} &= (e^{i\theta_1}tr + e^{i\theta_2}rt)(\overline{e^{i\theta_1}tr + e^{i\theta_2}rt}) \\ &= 2|t|^2|r|^2 + 2|r|^2|t|^2\frac{e^{i(\theta_1-\theta_2)} + e^{-i(\theta_1-\theta_2)}}{2} \\ &= 2|t|^2|r|^2 + 2|r|^2|t|^2\cos(\theta_1-\theta_2) \end{aligned}$$

Mach-Zehnder interferometer

- $$P_{10} = 2|t|^2|r|^2 + 2|r|^2|t|^2 \cos\theta$$
- $\theta = \theta_1 - \theta_2$ is the phase difference
- 50:50 beamsplitter have $|r| = |t| = \frac{1}{\sqrt{2}}$
- $$P_{10} = \frac{1}{2}(1 + \cos\theta).$$
- $$P_{01} = 1 - P_{10} = \frac{1}{2}(1 - \cos\theta)$$
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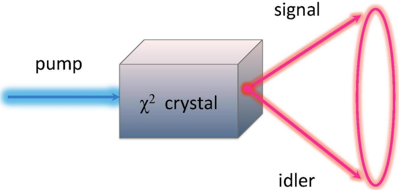
Single Photons?

- Spontaneous parametric down-conversion



Outline

Experimental Set-up

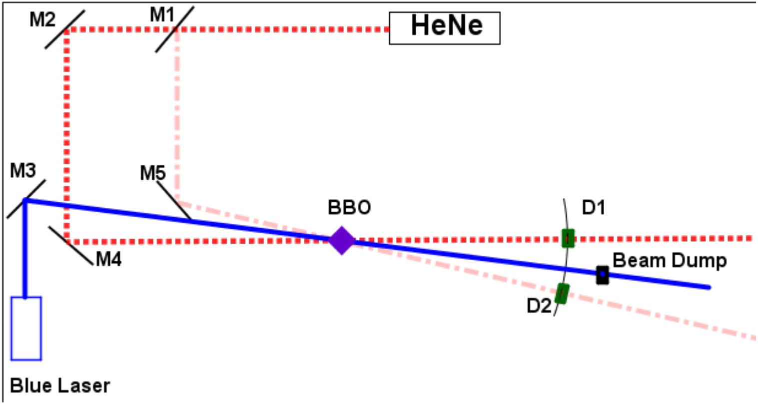


Figure: Using an arc to determine the locations of the detectors D1 and D2

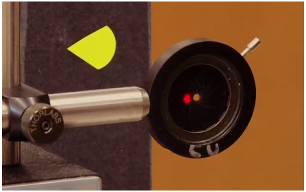
Experimental Set-up

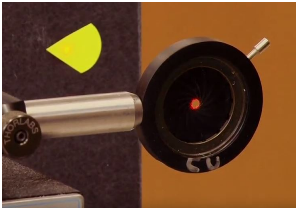
- First, we must assure that we are acquiring coincidence counts in our two detectors that is, they are equidistant from the BBO (Barium Borate) crystal.
- A 405 nm laser is carefully placed to go through the BBO crystal and by means of parametric down conversion, photon pairs are formed 3° apart to be detected in $D1$ and $D2$.
- With the use of a LabView program, our detectors let us know if there has been a photon pair detected in both detectors simultaneously.

Key Procedures

- Assure all pieces are the exact same height
- Assure the beam remains that height during its path entirety. (Iris iteration method with EVERY piece)
- Best to have beam remain parallel to holes in breadboard
- Use plumb-bob to accurately place pieces and align beams
- Alignment is done using the red beam to mimic the 405nm beams path
- Optimize coincidence counts

Iris

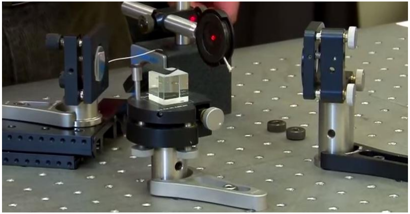




MZI initial set-up

- Placing the first beam splitter, assure the incident beam is reflected down its path of incidence and reflected perpendicular relative to incidence
- Assure reflected path is parallel to holes in table using iris iteration
- Place a mirror to reflect the initially transmitted beam parallel to the holes (iterate)
- The first reflected beam hits a mirror on top of a translational stage with a piezo electric to drive the stage very slightly forward, pushing the mirror slightly forward with a small voltage applied.

MZI initial set-up



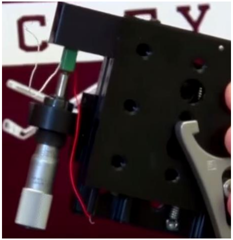
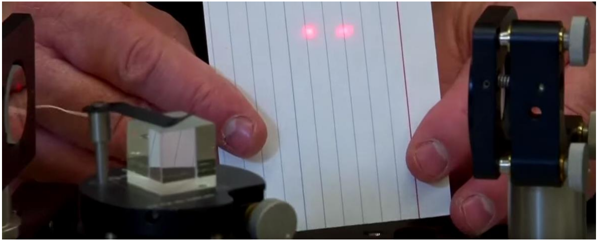


Figure: Piezo Driver in the Translational Stage

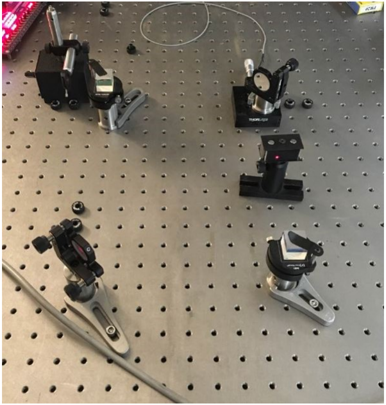
MZI final piece

- Place the final beam splitter where the two beams intersect in space.
- Similar to the previous iris iteration process to assure the beams are parallel with the holes and at the correct height
- With the first reflected path blocked, we can align the beam exiting the beam splitter
- Then blocking the first transmitted path, align the translational stage with mirror to superimpose the beam previously aligned and iterate.

MZI final piece



MZI final piece



MZI with white light

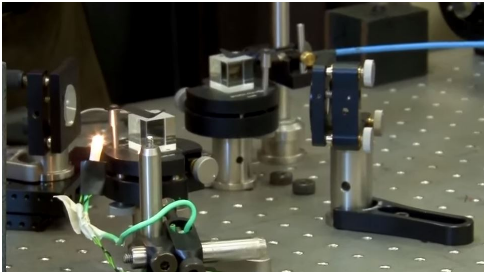


Figure: Both the bulb and Fiber Optic Cable are set up

MZI with white light

- Determine if the interferometer arms are the exact same length
- Placing a white light source in front of the interferometer and a spectrometer with fiber optic cable to receive the light at the end we can view the white light spectrum.
- If the arm lengths are very near identical, interference will begin.
- Translational stage can be slightly adjusted to an optimal interference of white light or just before that point.

MZI with white light

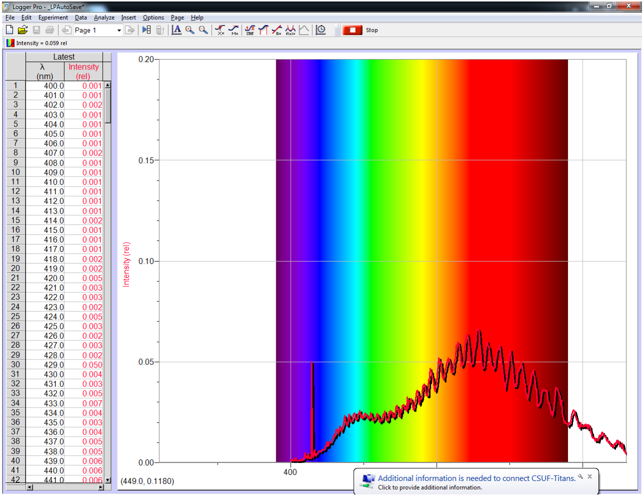
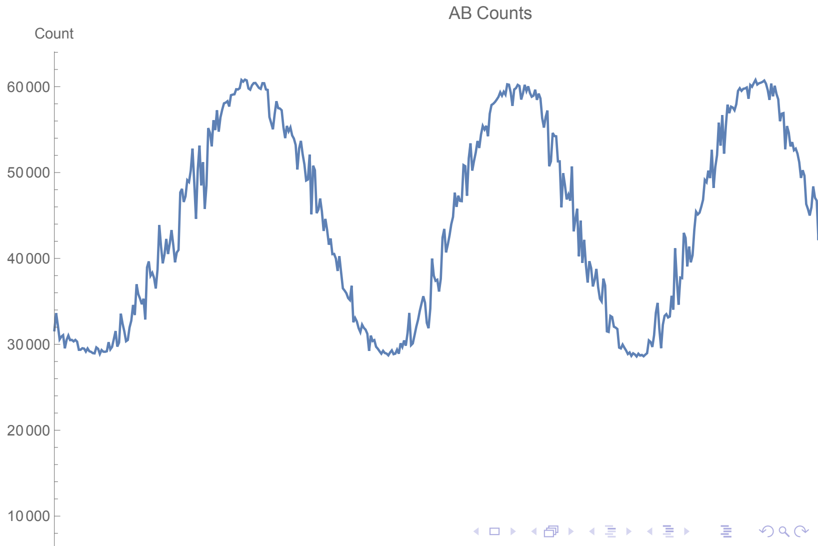


Figure: Some wavelengths interfering

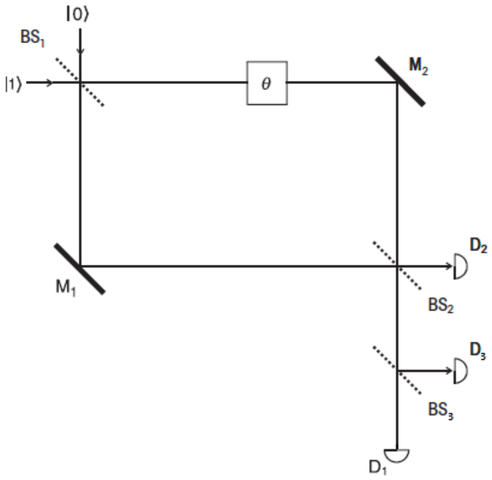
Results


physical channels
VISA resource name
STOP AND SAVE
Calibration Mode

Results

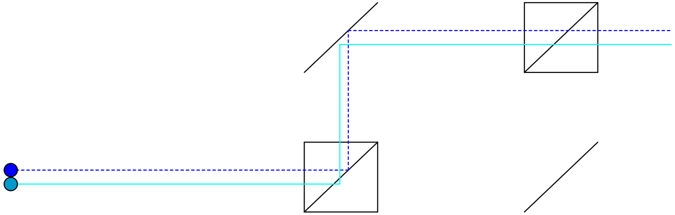


Biphoton Interference MZI

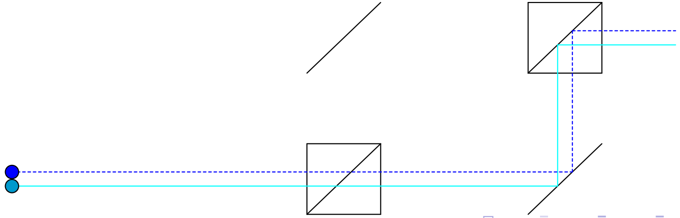


Biphoton Cases

Case 1: Both of the photons will go through one of the arms MZI.

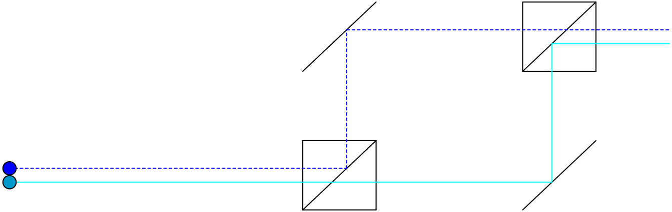


Case 2: Both of the photons will go through the other arm (different from Case 1) of the MZI.

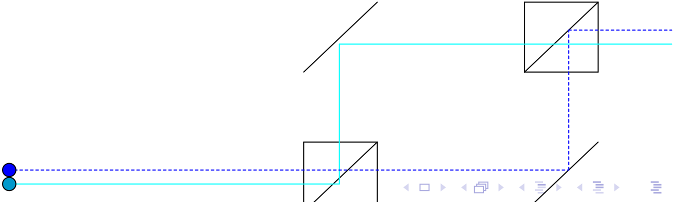


Biphoton Cases

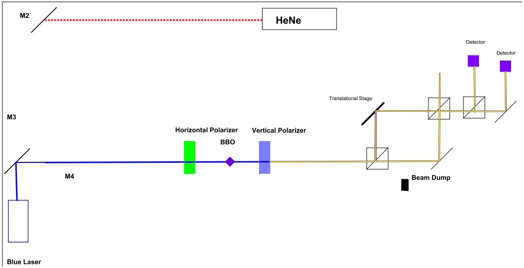
Case 3: One photon will go through one of the hands of the MZI and the other photon through the other hand of the MZI.



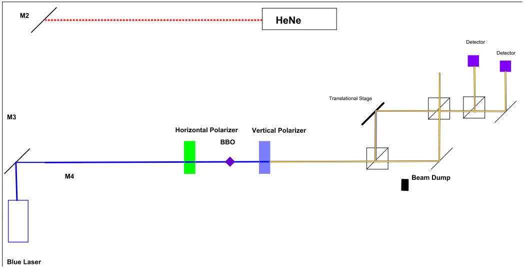
Case 4: Same as Case 3, but the photons pass though the other hand of the MZI.



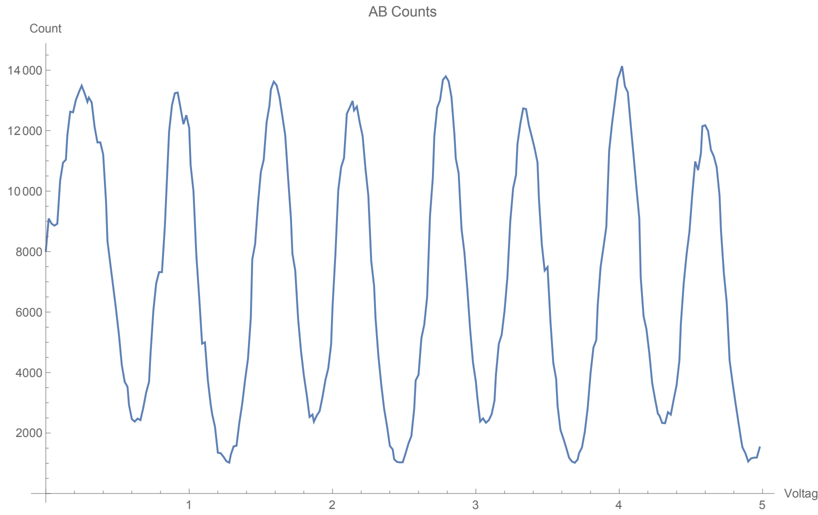
Complete set-up



Complete set-up



Results


AB Counts
Count
14 000
12 000
10 000
8000
6000
4000
2000
1
2
3
4
5
Voltag