EXPERIMENTS WITH DOWNCONVERTED PHOTONS: THE QUANTUM ERASER

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Abstract

This experiment investigates properties of light at the single photon level. We generate pairs of 915.8-nm photons through parametric downconversion by sending a beam of 457.9-nm light through a BBO crystal. These downconverted photons are detected using two avalanche photodiodes. We then create a distinguishable characteristic in one arm of a Mach-Zehnder interferometer by adding a half waveplate. This will destroy the single photon interference pattern that is observed when single photons are sent through an interferometer with indistinguishable arms. We will regain the interference pattern by adding a 45° polarizer in front of our avalanche photodiode. This polarizer effectively erases the distinguishing information added by the half waveplate.

I.1 Introduction:

Questions about the nature of light have intrigued physicists for centuries. While some prominent scientists, such as Newton, claimed that light is composed of particles, numerous experiments showed that light has wave-like properties. In 1905, Einstein showed that light is made up of discrete wave packets, which can be seen as analogues of particles. This means that, strangely enough, light must have properties of both waves and particles. This wave-particle duality of light has been the focus of many experiments, one of which will be discussed here.

I.2 Interference:

Interference is one of the basic properties of light waves. When shone through a solid barrier containing two slits, a beam of light will interfere with itself to produce a series of light and dark strips upon a target placed immediately behind the slits. The resulting pattern will not display the sum of the intensities that would occur if the light beam was sent through each slit separately. Instead, the pattern will display an intensity distribution given by the equation:

$$ P = |\Phi_1 + \Phi_2|^2, $$

where $P$ is the probability that light will strike the target at any given place and $\Phi_1$ and $\Phi_2$ are complex numbers giving the probability amplitudes that occur if the light beam is sent through only one slit or the other.

If large, solid objects, such as bullets, are shot through these same two slits, a different pattern will emerge on a screen placed behind the slits. Instead of the alternating strips of high and low intensity that were seen in the wave experiment, a smooth pattern will arise which can be explained by saying that the bullets had a certain
probability of traveling through either slit, and the pattern formed is simply the sum of these. Instead of showing alternating fringes, the distribution of bullets will be much smoother, with the most bullets hitting directly behind the region in between the two slits. The number of bullets hitting the screen decreases gradually as you move farther away from the portion of the screen directly behind the two slits. Because it is possible to see which slit an object the size of a bullet traveled through, the probability of a bullet hitting the screen at any given location can be determined by the equation:

\[ P = P_1 + P_2. \]  

In this equation, \( P_1 \) and \( P_2 \) are the probabilities of bullets traveling through either slit one or slit two to arrive at a given location on the target screen.

The property of interference is not strictly limited to light waves, however. It has also been shown to apply to light in its particle form. If single photons are shot at the two-slit setup, an interference pattern will appear, thereby showing that particle-like photons are capable of acting like waves. Although this is indeed a very odd result, even stranger discoveries can be made from this experiment. If a detector that is capable of observing which specific slit each photon travels through is introduced into the experiment, the interference pattern disappears and the pattern made by these photons will follow the probability distribution seen when the experiment was run with solid bullets. This result occurs because, with the detectors in place, we are able to determine the path taken by the photon, thereby eliminating the possibility of the photon taking both paths. Interference will only occur if the possible paths taken by the photons are indistinguishable from one another.\(^1\) This property will prove essential in running this experiment.

I.3 Polarization:

Another concept which is crucial to this experiment is that of polarization. Polarization refers to the alignment of the electric field associated with light waves. Assuming that the wave propagates along the z direction, this electric field can be expressed as the sum of its x and y components as follows:

\[ \vec{E} = E_0 \cos(kz-wt+\phi_1) \hat{i} + E_0 \cos(kz-wt+\phi_2) \hat{j}, \]  

where \( k = \frac{2\pi}{\lambda} \), \( w = \frac{2\pi}{T} \) is the angular frequency of the wave, and \( E_0 \) is the amplitude of the wave.

If \( \phi_1 = \phi_2 \), the two components are completely in phase; the wave is said to be linearly polarized, and the electric fields associated with the wave change magnitude and direction while staying in one plane. If \( \phi_1 - \phi_2 = \pm \frac{\pi}{2} \), the wave is said to be circularly polarized, and the electric field direction rotates in a transverse plane as the wave propagates while keeping the same magnitude as it moves forward. The electric field associated with a right circularly polarized wave can be written

\[ \vec{E} = E_0 \cos(kz-wt) \hat{i} + E_0 \sin(kz-wt) \hat{j}. \]  

If the two components of the electric field are out of phase by any other amount, the beam is said to be elliptically polarized. Elliptically polarized beams have electric fields which change both magnitude and direction as they travel through space.

Waveplates introduce a phase difference between the two components of a light wave’s polarization along the optical axes of the waveplate. Quarter waveplates add a phase difference of \( \frac{\pi}{2} \) between the two components of the wave’s polarization along the axes of the waveplate. Half waveplates add a phase difference of \( \pi \). Phase shifts can be
attained if the state of polarization is transformed such that it follows a closed path on the Poincaré sphere, which is shown in Figure 1. The poles of the sphere represent the two states of circular polarization, and points along the equator of the sphere represent states of linear polarization. All other points on the surface of the sphere represent elliptically polarized states.

![Figure 1: The Poincaré sphere displaying different states of polarization.](image)

Polarizers allow only light that is polarized along a certain plane to pass through them. If an incident light beam is not polarized at the same angle that the polarizer is set to, then only the component of the beam that is polarized at this angle will pass through. Waveplates and polarizers are two of the main tools used in this experiment.

II.1 Single Photon Interference Overview:

We create downconverted pairs of photons by sending a 457.9-nm beam of light, known as the pump beam, from an argon laser through a Beta-Barium Borate (BBO) crystal. Due to this crystal’s birefringence, some of the photons traveling through the crystal are converted into two separate photons. Energy and momentum must both be conserved during the downconversion process, so downconverted photons exiting the BBO must have energies summing to the energy of the parent photon. We concern ourselves only with the case in which the downconversion yields two identical beams of 915.8-nm photons. Despite the fact that the efficiency of downconversion is on the order of $10^{-10}$, our laser is powerful enough for a sufficient number of 915.8-nm photons to be created.² These photons will travel horizontally at ± 3 degrees from the original direction of the pump beam.

One of these beams of photons is termed the idler and is sent directly to an avalanche photodiode (APD) for detection. The other beam of photons, termed the signal, travels through a Mach-Zehnder interferometer before being detected by a separate APD. If the two arms of the interferometer are close enough in length so that it is not possible to know the path taken by a given photon, an interference pattern should be observed in the coincidences between the signal and idler photons as the path length of one arm of the interferometer is changed slightly.
II.2 Detecting Coincidences:

We detect coincidences to ensure that the photons we are measuring are of the specific downconverted type that we wish to deal with. If one photon from the signal beam and one from the idler beam are detected simultaneously, then we can be reasonably certain that they are both members of the same downconverted pair and that we are truly measuring single photons.

To detect these coincidences, we use a Time-to-Amplitude Converter (TAC), which is connected to the avalanche photodiodes used to detect the photons. One APD is connected directly to the “start input” of the TAC, while the other is connected to the “stop input” of the TAC by a 10-foot cable that adds a time delay of 15 ns to the signal. This delay cable is necessary because the electronics of the TAC are not capable of measuring simultaneous events. The TAC outputs a voltage which is proportional to the time difference between the start and stop inputs. Since photons coming from one of the detectors travel through a delay cable which adds 15 ns to their travel time, any photon pairs produced by downconversion should arrive at the TAC with a time difference of about 15 ns between them. Thus, signals sent out from the TAC that result from detecting downconverted pairs will all have approximately the same voltage.

We use a multi-channel analyzer to make a pulse-height histogram that plots the frequency with which signals of various voltages are output by the TAC. By looking at this histogram we can determine the range of voltages corresponding to TAC output signals from downconverted pairs. Since all of our downconverted photons arrive approximately 15 ns apart, and the time difference in arrival of any other photons could be anything, the voltage range of TAC corresponding to the range of time around 15 ns will appear as a peak in this plot, as can be seen in Figure 3. The TAC is connected to a Single Channel Analyzer (SCA), which allows us to look only at data located in a time window that we set from \( T \) to \( T + \Delta T \). Because the signal voltages output by the TAC are proportional to the difference in photon arrival times at the TAC, this time window can be viewed as a window that contains only the signals output by the TAC containing a certain range of voltages. We set this window to include only the TAC output signals representing downconverted pairs by looking at the histogram from the multi-channel
analyzer. Thus, a coincidence will be recorded if one photon from each detector reaches the TAC in a way such that the time difference between the two photons falls within the time window that we have specified. This will keep us from measuring accidental coincidences, such as those found outside of the peak in Figure 3. The SCA sends out only these voltage pulses from the TAC that fall within the correct time window as coincidences. These coincidences, along with single photon counts from our signal detector, are then counted using a computer program that I produced using Labview.

Figure 3: Histogram obtained using a multi-channel analyzer. Points along the x-axis represent the different voltages of signals output by the TAC.

III.1 Coherence Length:
Each photon can be seen as a wave packet that has a length given by

\[ l = c\Delta t = \frac{\lambda^2}{\Delta \lambda}, \]

where \( c \) is the speed of light, \( \lambda \) is the wavelength of the light, and \( \Delta \lambda \) is the uncertainty in this wavelength. This wave packet length, \( l \), is called the coherence length. \(^3\) If the difference in length between the two arms of an interferometer is less than the coherence length of the photon, then the two arms are said to be indistinguishable, since it is not possible to measure which path the photon took.

\( \Delta \lambda \) is determined by filters that are placed immediately in front of the detectors. In this experiment, we begin by placing 10-nm filters in front of both of the detectors, which gives us \( \Delta \lambda = 10 \) nm. These filters allow through only light with a wavelength that falls within a 10-nm range around our target wavelength of 915.8 nm. Using Equation 5, we get \( l = 84 \) µm for the length of the wave packet, which means that if we wish to obtain interference from our single photons, we must align our interferometer so that the path lengths are within 84 µm of each other. Although possible, this is an extremely difficult task to complete. When we record coincidences as the path length of one arm of the interferometer is slightly altered, we observe no interference pattern, as can be seen in Figure 4. Since we see no interference pattern in this data, it tells us that the two paths of the interferometer are not aligned to within 84 µm of each other. In this experiment, the path length of one arm of the interferometer is modified by fractions of a
wavelength at a time by applying a voltage to a piezo electric that is attached to one of the mirrors of the interferometer (See Figure 2). This voltage is applied using my Labview program which also counts the photon coincidences.

![Graph](https://via.placeholder.com/150)

**Figure 4**: Coincidences recorded vs. voltage (which is proportional to a change in path length) with 10-nm filters on both the signal and idler beams. In accordance with Poisson statistics, the error bars on this and all other graphs in this paper equal the square root of the number of counts.

We were able to make the alignment easier by exchanging the 10-nm filter in front of the idler beam detector for a 1-nm filter. Since we were measuring photon coincidences, it was not necessary to put the 1-nm filter in front of both detectors, or even the signal detector. If a 1-nm filter is placed in front of either detector, this will be the uncertainty in wavelength for either beam, because photons of a wavelength outside this 1-nm range will have their partner photons blocked by the 1-nm filter, even if they make it through the 10-nm filter themselves. This eliminates the possibility of photon pairs with wavelengths outside this 1-nm range being recorded as coincidences. The 1-nm filter gave us $\Delta \lambda = 1$ nm, and a coherence length $l = 840 \mu$m. Aligning an interferometer to this precision is not overly difficult, and using the same alignment as before, we were able to obtain an interference pattern in coincidences by slightly modifying one of the path lengths, since the two paths that could be taken by the single photons were indistinguishable. This pattern is shown in Figure 5.
III.2 Quantum Eraser:

The interference pattern that we gained by putting a 1-nm filter in front of the detector for the idler beam can be destroyed by once again making the two arms of the interferometer distinguishable from one another. This could be done in many different ways, but in this experiment, we placed a half waveplate in one of the arms. By turning this waveplate, we added a phase shift to the polarization of the photon in one path, while the polarization of photons in the other path remained constant. However, when the optical axis of the waveplate was aligned with the polarization of the photon, the polarization was not changed, and the two paths of the interferometer remained indistinguishable.

The quantum mechanical amplitude of a photon traveling through one arm of the interferometer can be represented by the equation

$$A = (TR)^{1/2} e^{i\delta} |V>, \quad (6)$$

where $T$ and $R$ stand for the transmission and reflection probabilities, which are each equal to one half for our beam splitters, $|V>$ represents the original wave function of the vertically polarized photon, and $\delta$ is a phase term given by the equation

$$\delta = (2\pi/\lambda)(\ell), \quad (7)$$

where $\ell$ is the path length of one arm of the interferometer, and $\lambda$ is the wavelength of the photon, which in our case is 915.8 nm. Since there is a slight difference in the path lengths of the two arms of our interferometer, photons traveling through different arms of the interferometer will have different values of $\delta$, and thus, different amplitudes. We define the value of $\delta_i$ for the entire interferometer to be

$$\delta_i = \delta_1 - \delta_2 = (2\pi/\lambda)(\ell_1 - \ell_2), \quad (8)$$

If the two paths of the interferometer are indistinguishable, the probability of detecting a photon traveling through the interferometer is the sum of the two amplitudes squared:

$$P = |A_i + A_2|^2. \quad (9)$$

In order to determine this probability, we begin by defining a term $A$:

$$A = A_1 + A_2 = (TR)^{1/2}(e^{i\delta} |V> - e^{-i\delta} |V>). \quad (10)$$

The probability of detecting a photon is then equal to this term squared,

$$P = A*A = 2TR(1+\cos \delta).$$
\[ = \frac{1}{2}(1 + \cos \delta). \]  

Equation (11)

We can see from this equation that the probability of detecting a photon changes as \( \delta \) changes, and thus as the difference in path length between the two arms of the interferometer changes. Therefore, by changing the path length of one arm of the interferometer, we can change the probability of detection from 0 when \( \cos \delta = -1 \), to 1 when \( \cos \delta = 1 \). When we applied an increasing voltage to our piezo electric stage, the path length of one arm was changed, and we observed the interference pattern in detected coincidences that can be seen in Figure 6. Alignment problems probably resulted in the coincidence counts not going to zero at the minima.

![Figure 6](image)

Figure 6: Coincidences recorded as one path of the interferometer is varied, and the two possible paths of the interferometer are indistinguishable.

By rotating the half waveplate by 45°, we were able to make the two paths distinguishable. As we began to rotate this waveplate, we observed lower and lower visibility in our interference fringes because fewer and fewer of the photons taking this path had the same polarization as photons traveling through the other path. The visibility of an interference pattern can be given by the equation

\[ V = \frac{C_{\text{max}} - C_{\text{min}}}{C_{\text{max}} + C_{\text{min}}} \]  

where \( C_{\text{max}} \) is the maximum number of counts collected, and \( C_{\text{min}} \) is the minimum number of counts collected.

The probability of detecting a photon with the waveplate turned to one of these partially distinguishable angles can be written

\[ P = 2TR[1 + \cos(2\phi) \cos \delta] \]

\[ = \frac{1}{2}[1 + \cos(2\phi) \cos \delta], \]  

Equation (13)

where \( \phi \) is the angle at which the half waveplate is set. This equation works in general for this experimental set-up. Notice that if \( \phi \) is set to 0°, we get the equation for completely indistinguishable paths. This equation also works for completely distinguishable paths.
Eventually, we got to a point (when the half waveplate was rotated by 45°) where the polarization of photons traveling through the two arms of the interferometer were perpendicular to each other. This means that a photon leaving one arm of the interferometer was vertically polarized, while a photon that traveled through the other arm was horizontally polarized. This made it possible to detect with certainty which path the photon took and caused our interference fringes to disappear. The probability of detecting a photon coming out of an interferometer whose paths are distinguishable can be written,

\[
P = |A_1|^2 + |A_2|^2 = 2TR = \frac{1}{2}.
\]  

(14)

So, if the two paths are distinguishable, we expect to see no oscillations in detected coincidences, but instead a constant number of coincidences that is equal to half the maximum number of counts that we obtained in our interference pattern resulting from indistinguishable paths. Figure 7 shows our data taken with distinguishable paths. We obtained a weighted straight line fit equal to a constant of 14.1 ± 3.6. This is somewhat less than the constant offset of 19.4 ± 4.4 that we obtained for our original interference pattern, yet it is within the range of error that these two constants are equal. It is also possible that these two values may be unequal due to extra absorption of the half waveplate when it is set to 45°. Slight oscillations that may be seen in our data are most likely a result of imperfect optical alignment, although when we attempted to fit a sine curve to this data, we obtained a curve with a visibility of 0.11 ± 0.35, which is consistent with this data being completely free from oscillations. Our interference pattern taken with the arms of the interferometer being indistinguishable yielded a visibility of 0.52 ± 0.28.

![Figure 7: Coincidences recorded while the two paths of the interferometer are made distinguishable by a half wave plate.](image-url)
We were able to regain the interference pattern without removing the distinguishing feature from the interferometer. We erased this distinguishing information simply by placing a polarizer set to 45° after the interferometer and before the APD that detects the signal photons. Since a polarizer set to 45° treats horizontally and vertically aligned photons identically, it was no longer possible to tell which path a photon took through the interferometer by the time it reached the detector. This meant that we were once again able to observe an interference pattern when we measured coincidences between the signal and idler beams as the path length of one leg of the interferometer was varied slightly. However, since the photons were now traveling through a polarizer which blocked half of their amplitude, the interference pattern theoretically should have had only half of its original amplitude. In Figure 8, we have fit a sine curve to our data and obtained a constant offset of 8.0±1.9, which is a little less than half of our original offset, and slightly more than half of the offset for the data in which the interferometer paths were made distinguishable. Once again, this constant offset being one-half of each of the two previous offsets is within the range of experimental error. We found the visibility of this pattern to be 0.40±0.34. The probability leading to this pattern is given by the equation

\[ P = \frac{1}{4}(1+\cos \delta). \]

Figure 8: Coincidences recorded after a polarizer has erased the information that allowed us to distinguish between the two paths of the interferometer.

Throughout this entire process, we were still only able to observe interference if the coherence length of the wavepacket was smaller than the difference in length between the two arms of the interferometer. Since a waveplate has a very different index of refraction from air, inserting a half waveplate into our interferometer changed the optical path length of the arm in which it was located. This made it necessary to add a quarter waveplate set to 0°, so as not to change the polarization of photons taking this path, to the
arm of the interferometer not containing the half waveplate at the same time that we added the half waveplate. Since half waveplates and quarter waveplates have almost identical indices of refraction, the path lengths of the two arms of the interferometer remained equal. Thus, the half waveplate made the two arms of the interferometer distinguishable only by modifying the polarization of the photons.

![Diagram of experimental set-up](image)

Figure 9: Experimental set-up for the quantum eraser.

IV.1 Conclusions:

This experiment has helped to show some fundamental properties of quantum mechanics, most notably the idea of indistinguishability. The fact that an interference term often arises when an object is presented with two indistinguishable choices is of extreme importance in our world. Although forms of this experiment have been performed before in large laboratory settings, we have begun the process of making them simple enough to run as demonstrations in introductory physics courses. In the future, we hope to add more experiments like this to our repertoire and continue to simplify this and other experiments dealing with single photons. We would also like to clean up our data, so that we can make the observation of these quantum mechanical principles even more convincing.

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References: