## 1. Time Correlated Single Photon Counting Experiment

In **quantum two-slit interference** experiment, we can use ideas similar to Time Correlated Single Photon Counting (TCSPC) and **accumulate particles**(photons or electrons) in **time bins** (for example 50 time bins) within a **single period** of the source signal, as particles arrive one by one from the slit to a particular location in detector (screen), particles arrive in different periods, they are accumulated in time bins corresponding to one single period. [ **mod(t0, T0)** where T0=signal period and t0=arrival time at detector ].

This idea probably uses **principle of demodulation**? In classical two-slit interference experiment, the source light signal is represented by $S(t) = A(t)\cos(\omega_0 t + \theta(t)) = I(t)\cos(\omega_0 t) + Q(t)\sin(\omega_0 t)$ and when this signal arrives at the detector from the two slits and interfere, travel different distances, rods and cones in our eyes respond to the source wavelength and then perhaps demodulate the baseband signal $\sqrt{(I^2(t) + Q^2(t))}$ to produce the **interference pattern**. Similar ideas can be used for time bins accumulation in quantum two-slit interference experiment. Single photons from 2 slits arrive at detector location, one at a time and we can accumulate them using time bins inside carrier period to produce the classical signal over time, and this accumulated signal retains baseband amplitude/phase modulation and demodulated by our eyes.

**Let us assume** the source light signal wave $S(t)$ of frequency $f = \frac{c}{\lambda}$ and maximum amplitude $A$, is composed of very large number of particles called **photons**, which are perhaps like **rectangular** pulses, with time-width $dt << T = \frac{1}{f}$ and amplitude $dA << A$. The source light signal $S(t) = A(t)\cos(\omega_0 t + \theta(t)) + A_{min}$ is modeled as a **discrete summation** of rectangular pulses, one for each photon, which add together to form $S(t)$ giving the **appearance** of a continuous waveform, while it may be a **discrete** summation of photons. When we observe a sine wave in a CRO, it may look continuous, but underlying hardware has **finite rise time** and **bandwidth**, hence if $dt, dA$ are **much smaller** than the smallest time duration and smallest amplitude we are able to measure so far, we **may miss** the finite width and amplitude of each photon.

$$S(t) = A(t)\cos(\omega_0 t + \theta(t)) + A_{min} \approx \sum_{p=0}^{P} N(p)[rect(\frac{(t - \frac{dt}{2} - p * dt)}{dt})dA] \tag{1}$$

where $N(p) = \frac{S(p*dt)}{dA}$ is the number of photons in any interval $p * dt$ and $P = \frac{T}{dt}$ and $T$ is the total signal duration. **We assume** that this signal $S(t) = A(t)\cos(\omega_0 t + \theta(t)) + A_{min}$ has a **DC offset** $A_{min}$, such that **number of photons is always positive** at any time instant in the signal. Note this is a **hypothetical** model, as an example, it is **not** implied that this is the **only** model for a real world sine wave.

Within a single period $T = \frac{1}{f}$ of this signal, we have a **large number of photons** in the **classical** experiment, which arrive at a specific detector location from 2 slits and add as per classical interference equation [**derived in section 1.2**]. Then our eyes demodulate the baseband signal to produce the **interference pattern**. Rods and cones in our eyes **may not respond to the DC term** $A_{min}$, so we **never see** any DC offset in the light wave.

In the **quantum two-slit interference** experiment, the only **difference** is that the source light **intensity is so low** that, within a single period $T = \frac{1}{f}$ of the signal, there are **very few photons** and in some periods, there is NO photon, in some periods there is only one photon. If we use **Time Correlated Single Photon Counting** to accumulate these photons in time bins, explained later in this section, then particles add up in time bins and produce the interference pattern.

In the case of **Tonomura's quantum two-slit interference** experiment with electrons, the **electrons accumulate over time** to gradually form an interference pattern on the monitor (similar to a long exposure with a photographic film). This is similar to using **Time Correlated Single Photon Counting** to accumulate them in time bins, as a positive number and produce the interference pattern. (**Video of Tonomura experiment**), (link) and (link)

The Interference Fringes in **my simulation** of 2-slit quantum interference experiment are very **similar** to interference fringes in Tonomura experiment.[ (My Interference Fringes), (Tonomura Interference Fringes)]

**Video tutorial** for 2-slit quantum interference simulation using Time Correlated Single Photon Counting (TCSPC) is here. (link)

**My simulation** of 2-slit quantum interference experiment uses **classical mechanics** plus **coin toss probability** (CM-CTP) model, where the coin toss probability is used **only to choose** a screen location for each arriving particle at slit. The reason we need to use CTP is because each arriving particle is **scattered** either by slit edges or by air particles. [Each cubic meter of air on Earth contains about $10^{25}$ molecules (standard atmosphere)(link) and lowest vacuum achieved so far is $10^{-13}$ Torr, which is $\frac{1}{760}$ of standard atmosphere. This means **lowest vacuum achieved** so far is $\frac{10^{25} * 10^{-13}}{760} = 10^9$ **molecules** in 1 cubic meter. (link) ]

My simulation **does not** use Copenhagen Interpretation of QM with metaphysical unreal probability wave functions and wave function collapsing at detector where particle is observed, which is "Observation creates Reality" and also my simulation **does not** use Uncertainty principle.

As we keep running simulation, more and more Accumulated particles will continue to retain sinusoidal interference pattern, but will saturate screen display because they exceed max value 256. Same thing happens with **Tonomura** electron interference experiment, so they cut off video after a short time. (link)

The **point** I am trying to make is this: In single particle interference experiments like Tonomura's, bright and dark **alternating fringes** can be explained by my **non-QM** ideas. I am **NOT** trying to explain **exact** fringe pattern!

The classical theory expects 2 bright lines a little away from slit, straight from source to slit to screen and NO interference. What **my simulation** does produce is brightish and darkish **alternate fringes**, with non-QM ideas.

Note that I am NOT saying this is what **exactly** happens in classical and Tonomura single particle experiments. It is **enough** for me to produce **alternating** bright and dark fringe pattern in my simulation, while classical theory expects 2 bright lines a little away from slit, straight from source to slit to screen.

This means, **given an observation** of alternating bright and dark fringe pattern in a single particle experiment, there may be **several** explanations for that observation and I have produced a **non-QM** explanation which is **simpler**.

**Yet to Understand: How does screen or photographic film do TCSPC? Human eyes can do this, but screens?** Photographic film or plate used in electron interference experiment, probably acts as a bandpass filter to select electron wave frequency band, like rods and cones in eyes select optical wavelengths? and does TCSPC?

### *1.1. Standard Time Correlated Single Photon Counting Experiment*

Time Correlated Single Photon Counting experiment is described here for a different application. (link)

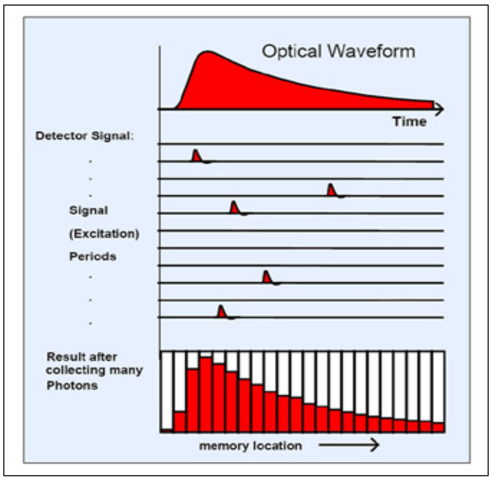


Figure 1:

**Time Correlated Single Photon Counting** (TCSPC) has been one of the best ways of measuring fluorescence decay times since the method was conceived in 1961 by Bollinger and Thomas [1]. The principle of time correlated single photon counting is the detection of single photons and the **measurement of their arrival times** in respect to a **reference signal,** usually the light source. This technique is a statistical method and high repetitive light source is needed to accumulate a sufficient number of photon events for a required statistical data precision. The important features of the method are high sensitivity and accuracy with picosecond time resolution.

**Measurement Principle**

Time-Correlated Single Photon Counting is based on the detection of single Photons of periodical light signal, the measurement of the **detection times of the individual photons** and the **reconstruction of the waveform** from the individual time measurements. The method makes use of the fact that for low level, high repetition rate signals the light intensity is usually so low that the probability of detection one photon in **one signal period** is much less than one. Therefore, the detection of several photons can be neglected and the principle shown in the figure below can be used: The detector signal consists of a train of randomly distributed pulses due to the detection of the individual photons. There are many signal periods without photons, other signal periods contain one photon pulse. Periods with more than one photons are very rare. When a photon is detected, the time of the corresponding detector pulse is measured. **The events are collected in memory by adding a '1' in a memory location with an address proportional to the detection time.** After many photons the histogram of the detection times, i.e. the waveform of the optical pulse, builds up in the memeory. Although this principle looks complicated at the first glimpse, it is very efficient and accurate for the following reasons: The accuracy of the time measurement is not limited by the width of the detector pulse. Thus, the time resolution is much better then with the same detector used in front of an oscilloscope or another linear signal acquisition devicee. Furthermore, all detected photons contribute to the result of the measurement.

### *1.2.* ***Classical two slit interference equations derivation***

We will derive equations for classical two slit interference pattern for a continuous wave light source signal $S(t) = A(t)\cos(\omega_0 t + \theta(t)) + A_{min}$ where $\omega_0 = 2\pi f_0$ is the signal angular frequency and $\theta(t)$ is the signal phase. It arrives in 2 slits $S_1$ and $S_2$ spaced at distance $d$, at the same time and then travels to a detector (screen) placed at a distance of $L$ from the slit plane. Let a point P at the detector be at a distance of $d_1 = \sqrt{(L^2 + (x - \frac{d}{2})^2)}$ from slit $S_1$ and distance of $d_2 = \sqrt{(L^2 + (x + \frac{d}{2})^2)}$ $d$ from slit $S_2$, where $x$ is the vertical distance of P from the center of slit plane.

Given that $I(t) = A(t)\cos(\theta(t))$, $Q(t) = -A(t)\sin(\theta(t))$, we will assume $S(t)$ as the **signal** arriving at both slits and the signal at **detector** location P is given by **D(t)** and we can write as follows, including light signal **attenuation term** $\frac{1}{4\pi d_1^2}$

$$
\begin{aligned}
S(t) &= A(t)\cos(\omega_0 t + \theta(t)) + A_{min} \\
S(t) &= I(t)\cos(\omega_0 t) + Q(t)\sin(\omega_0 t) + A_{min} \\
D(t) &= \frac{S(t - \frac{d_1}{c})}{4\pi d_1^2} + \frac{S(t - \frac{d_2}{c})}{4\pi d_2^2} \\
D(t) = \frac{I(t - \frac{d_1}{c})}{4\pi d_1^2}\cos(\omega_0(t - \frac{d_1}{c})) &+ \frac{Q(t - \frac{d_1}{c})}{4\pi d_1^2}\sin(\omega_0(t - \frac{d_1}{c}) \\
+\frac{I(t - \frac{d_2}{c})}{4\pi d_2^2}\cos(\omega_0(t - \frac{d_2}{c})) &+ \frac{Q(t - \frac{d_2}{c})}{4\pi d_2^2}\sin(\omega_0(t - \frac{d_2}{c}) + 2A_{min}
\end{aligned}
\tag{2}
$$

We can write above equation concisely as follows.

$$
\begin{aligned}
D(t) &= I_D(t)\cos(\omega_0 t) + Q_D(t)\sin(\omega_0 t) + 2A_{min} \\
I_D(t) &= \frac{I(t - \frac{d_1}{c})}{4\pi d_1^2}\cos(\frac{\omega_0 d_1}{c}) - \frac{Q(t - \frac{d_1}{c})}{4\pi d_1^2}\sin(\frac{\omega_0 d_1}{c}) + \frac{I(t - \frac{d_2}{c})}{4\pi d_2^2}\cos(\frac{\omega_0 d_2}{c}) - \frac{Q(t - \frac{d_2}{c})}{4\pi d_2^2}\sin(\frac{\omega_0 d_2}{c}) \\
Q_D(t) &= \frac{I(t - \frac{d_1}{c})}{4\pi d_1^2}\sin(\frac{\omega_0 d_1}{c}) + \frac{Q(t - \frac{d_1}{c})}{4\pi d_1^2}\cos(\frac{\omega_0 d_1}{c}) + \frac{I(t - \frac{d_2}{c})}{4\pi d_2^2}\sin(\frac{\omega_0 d_2}{c}) + \frac{Q(t - \frac{d_2}{c})}{4\pi d_2^2}\cos(\frac{\omega_0 d_2}{c})
\end{aligned}
\tag{3}
$$

Rods and cones in our eyes respond to the source wavelength $\lambda = \frac{c}{f_0}$ and then perhaps **demodulate the baseband signal** $B(t) = \sqrt{(I_D^2(t) + Q_D^2(t))}$ to produce the **interference pattern**.

Note that rods and cones in our eyes **may not respond to the DC term** $2A_{min}$ which is a constant, so we ignore this term.

$$
\begin{aligned}
B^2(t) &= (I_D^2(t) + Q_D^2(t)) = B_1(t) + B_2(t) \\
B_1(t) &= (\frac{I(t-\frac{d_1}{c})}{4\pi d_1^2})^2 + (\frac{Q(t-\frac{d_1}{c})}{4\pi d_1^2})^2 + (\frac{I(t-\frac{d_2}{c})}{4\pi d_2^2})^2 + (\frac{Q(t-\frac{d_2}{c})}{4\pi d_2^2}|)^2 \\
B_2(t) &= \frac{I(t-\frac{d_1}{c})}{4\pi d_1^2}\frac{Q(t-\frac{d_1}{c})}{4\pi d_1^2}\cos(\frac{2\omega_0 d_1}{c}) + \frac{I(t-\frac{d_2}{c})}{4\pi d_2^2}\frac{Q(t-\frac{d_2}{c})}{4\pi d_2^2}\cos(\frac{2\omega_0 d_2}{c}) \\
&+ \frac{I(t-\frac{d_1}{c})}{4\pi d_1^2}\frac{I(t-\frac{d_2}{c})}{4\pi d_2^2}\sin(\frac{\omega_0(d_1+d_2)}{c}) + \frac{I(t-\frac{d_1}{c})}{4\pi d_1^2}\frac{Q(t-\frac{d_2}{c})}{4\pi d_2^2}\cos(\frac{\omega_0(d_1+d_2)}{c}) \\
&+ \frac{Q(t-\frac{d_1}{c})}{4\pi d_1^2}\frac{I(t-\frac{d_2}{c})}{4\pi d_2^2}\cos(\frac{\omega_0(d_1+d_2)}{c}) - \frac{Q(t-\frac{d_1}{c})}{4\pi d_1^2}\frac{Q(t-\frac{d_2}{c})}{4\pi d_2^2}\sin(\frac{\omega_0(d_1+d_2)}{c})
\end{aligned}
\tag{4}
$$

Let us assume $A(t) = 1$ for the light source and $\theta_t = 0$ without loss of generality. Hence $I(t) = 1, Q(t) = 0$. We can see that $I(t-\frac{d_1}{c}) = I(t-\frac{d_2}{c}) = 1$ and $Q(t-\frac{d_1}{c}) = I(t-\frac{d_2}{c}) = 0$. Hence we can write

$$
\begin{aligned}
B^2(t) &= (I_D^2(t) + Q_D^2(t)) = B_1(t) + B_2(t) \\
B_1(t) &= (\frac{1}{4\pi d_1^2})^2 + (\frac{1}{4\pi d_2^2})^2 \\
B_2(t) &= \frac{1}{4\pi d_1^2}\frac{1}{4\pi d_2^2}\sin(\frac{\omega_0(d_1+d_2)}{c}) \\
B(t) = \sqrt{(B_1(t)+B_2(t))} &= \sqrt{(\frac{1}{4\pi d_1^2})^2 + (\frac{1}{4\pi d_2^2})^2 + \frac{1}{4\pi d_1^2}\frac{1}{4\pi d_2^2}\sin(\frac{\omega_0(d_1+d_2)}{c})}
\end{aligned}
\tag{5}
$$

We can see that the equation for $B(t)$ has a **sinusoidal interference pattern** as a function of distance $d_1, d_2$.

**Verify using Matlab simulations** that above equation for $B(t)$ produces a classical interference pattern.

### *1.3. Srinivas explanation of my simulation of two-slit interference*

But the idea seems to be to have an interval T0, and then to send particles and then accumulate at the screen in bins module T0. Suppose all sampleNum were 0, Now any row,col will get up to two bins populated, which will be separated depending on the phase difference of the two paths to that row, col. If there is no phase difference of the two paths, you will fill only one bin for that position. Now you have a distribution on sampleNum, and what you will populate at row,col will be a **circular convolution** of this distribution with the two point distribution we got earlier. Now on this, you apply this rule of considering a point to have hits if (1) all bins have a non-zero number , and (2) take the number of hits to be the maximum.

Now if sampleNum is always a fixed value, you will never meet criterion (1) for any point. If sampleNum has a distribution, which is uniform, you will probably meet this for all points. This asin() function that you are using to get sampleNum means that sampleNum has a **distribution concentrated around the middle**, and after the **convolution**, the **out of phase points have a better chance of meeting criterion (1)**. And if you see your graph, you see that you have the black line in the centre, compared with a usual interference pattern where the centre line has constructive interference and not a zero.