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Event-Based Simulation Mach-Zehnder Interferometer with Dynamic Absorber to Study the Wave-Particle Duality

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Abstract. The simulation of Mach-Zehnder Interferometer with a dynamic absorber (periodic chopper) have been done. The simulation did 100000 events and only used particles (photon), not wave. Simulation algorithm applied various probability of particles passed through the absorber; 0, 0.25, 0.50, 0.75 and 1. Those probabilities influenced the intensity of interference and showed the nature of wave-particle duality. The wave-nature was shown by the interferences, while the particle-nature is revealed by the decreasing of interference intensity as the absorber placed in one of the two beam paths.

1. Introduction

In quantum theory, particles show the nature of waves and particles [1]. It is well known as wave-particle duality. Its phenomenon is explained by Young double-slit experiment. The wave-nature is presented by interferences, while the particle-nature is shown by which path particles take [2]. Several number of experiments were proposed to study the wave-particle duality. One of them was known as a “which-path” (welcher Weg) experiment such as Einstein’s recoiling slit and Feymen’s Light Microscope. In those experiments, the wave-particle duality information cannot be collected simultaneously. Interferences were formed after a collection of particles passed through the slits, if the which-way detector was then added into the experiment (to gain the particle’s path information), consequently the interferences destroyed [3,4].

Some other proposed experiment was Wheeler delay choice experiment [5] and Greenberger *et al* neutron interferometry experiment with absorber [6,7]. In Greenberger *et al* experiment, an absorber was placed in one of the two beam paths to attenuate the beam. The beam attenuation showed the particle’s location, which path the particles took. Later on, Rauch *et al* did neutron interferometry experiments with various kinds of absorbers (static and dynamic) were placed in one of the two beam paths [8-10]. This neutron interferometry experiment is much similar with Mach-Zehnder Interferometer (MZI) experiment; A neutron source produced neutron beam. At the first beam splitter, the beam was split into two coherent beams and directed to the second beam splitter. At the second beam splitter, the beams interfered.

Although quantum mechanics provides a theory to compute the frequency for observing different types of events, it does not describe how each individual event (particle) yield output data in the experiment. For example, how each particle in the double-slit experiment contributes to the interference pattern. The event by event method adequate to simulate the quantum phenomenon, event by event. The method uses particles only, no wave. Even though the method does not rely with quantum theory, it produces the same data type as the data collected in laboratory experiments.

This paper performed an event-based simulation of Mach-Zehnder Interferometer with a dynamic absorber to study the wave-particle duality as did by Rauch *et al*. The photon source, beam splitters (BS), mirrors, detectors and a dynamic absorber were taken into the simulation. The diagram of

Mach-Zehnder Interferometer with a dynamic absorber was shown di Fig. 1. The particles were produced by a photon source (not shown in the diagram) and sent to beam splitter 1 (BS 1). In BS 1 the particles were sent to path b_0 or b_1 and directed to beam splitter 2 (BS 2) by mirrors. In BS 2 the particles recombined and interfered. At the end, they were counted by detectors N_2 and N_3. When the dynamic absorber (a periodic chopper) placed on path b_1, the number of particles in path $b_1$were reduced because the periodic chopper absorbed it. Besides attenuating the particles, the absorber acted as a detector and counted the number of particles which were absorbed.

This paper explained the detail of event by event method in section 2, as well as the theory of MZI with an absorber. The method and results were displayed in section 3 and 4. The simulation results were compared with the theoretical calculation. The conclusion was given in section 5.

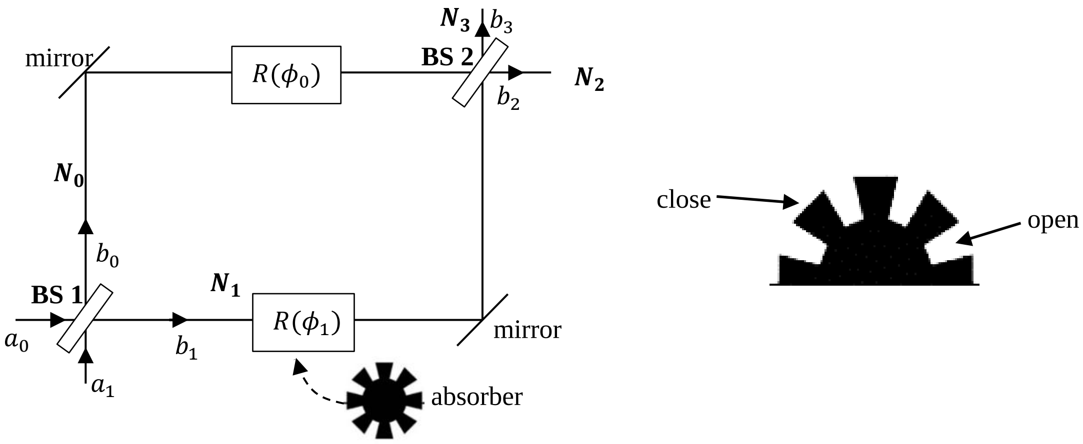

Fig. 1. The diagram of Mach-Zehnder Interferometer with an absorber (periodic chopper). The diagram consists of a source (not shown), two beam splitters, two mirrors, two passive devices $R(\phi_0)$ and $R(\phi_1)$, a dynamic absorber and detectors (not shown).

2. The Theory

Event by event methods was developed by Hans de Raedt *et al* in 2005. The method is described in term of source, events, messages, processing unit and detector. The source produces photons, before producing it the source is waiting until the previous photon has been processed by detector. Events are correlated to the detection of photon in the detector. Messages are properties that are carried by each photon, every photon is a messenger. The Processing unit is the beam splitter which process the events and message. Detector is a unit which detects the photon [11,12].

2.1 Beam Splitter

In this simulation, a beam splitter is performed by a Deterministic Learning Machine (DLM) which simulate the beam splitter event by event. DLM has three stages; the first stage is an input channel (frond-end), second stage is a transformation stage and the third stage (back-end) is an output channel. At the beginning, some initial conditions are set up;

- The internal two-dimensional vector $x_{i,n}$ where $x_{i,0} \geq 0$ for $i = 0$, and $n \geq 0$. n is labels the different event. So that $x_0 = \left(x_{0,0}, x_{0,1}\right) = (r, 1 - r)$, where $x_{0,0} + x_{0,1} = 1$ and r is a random number in the interval of [0,1].
- The register $Y_0 = (\cos\psi_0 , \sin\psi_0)$ and $Y_1 = (\cos\psi_1 , \sin\psi_1)$. The angles ψ_0 and ψ_1 are gained from a uniform random number in the interval of [0,360].

At $(n + 1)^{\text{th}}$ event, the first state receives incoming message y_{n+1} on neither channel 0 or 1, never on both channel simultaneously. When the message arrives in input channel 0 or 1, then the input channel 0 receives $(\cos\phi_0 , \sin\phi_0)$ with probability p_0, therefore input channel 1 receives

$(\cos\phi_1, \sin\phi_1)$ with probability $p_1 = 1 - p_0$. The first stage stores the message y_{n+1} in its internal register $Y_k = (Y_{0,k}, Y_{1,k})$, where $k = 0(1)$ if the event occurs in channel 0(1). The internal vector x are update according to the rule

$$x_{i,n+1} = \alpha x_{i,n} + 1 - \alpha, \qquad \text{if } \ i = k, \tag{1}$$
$$x_{i,n+1} = \alpha x_{i,n}, \quad \text{if } \quad i \neq k, \tag{2}$$

where $0 \leq \alpha \leq 1$ is the parameter that controls the speed of learning process.

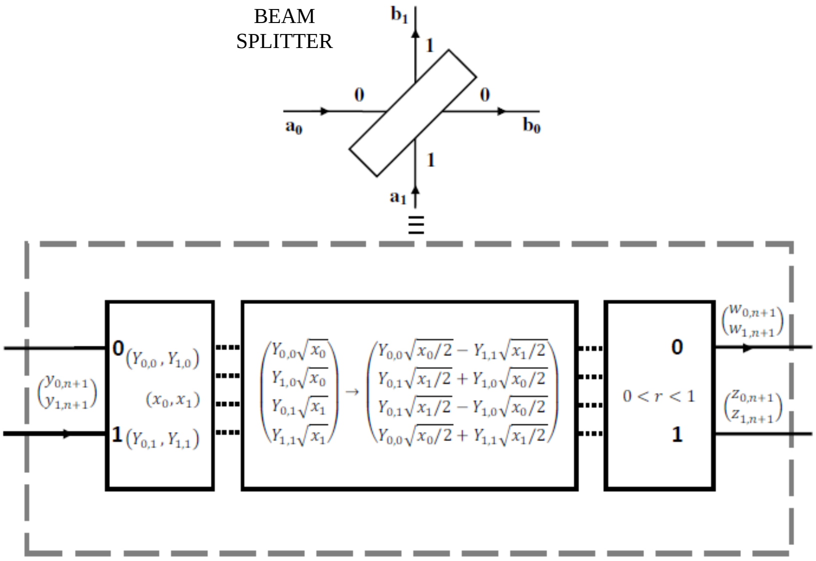

Fig. 2. Diagram of a Deterministic Learning Machine (DLM). The DLM performs a single photon beam splitter. The solid lines represent input and out channels of the DLM. The dashed lines indicated the data flow within the processor.

The second stage or the transformation stage, the input values are transformed according to the following rule

$$\frac{1}{\sqrt{2}}\begin{pmatrix} Y_{0,0}\sqrt{x_0} - Y_{1,1}\sqrt{x_1} \\ Y_{0,1}\sqrt{x_1} + Y_{1,0}\sqrt{x_0} \\ Y_{0,1}\sqrt{x_1} - Y_{1,0}\sqrt{x_0} \\ Y_{0,0}\sqrt{x_0} + Y_{1,1}\sqrt{x_1} \end{pmatrix} \leftarrow \begin{pmatrix} Y_{0,0}\sqrt{x_0} \\ Y_{1,0}\sqrt{x_0} \\ Y_{0,1}\sqrt{x_1} \\ Y_{1,1}\sqrt{x_1} \end{pmatrix} \tag{3}$$

as shown in Fig. 2. The third stage is called back end. It responds to the input event by sending a messenger which is carrying message w_{n+1} through output channel 0 if $w_{0,n+1}^2 + w_{1,n+1}^2 > r$, where r is a uniform random number in the interval [0,1]. Otherwise back end sends message z_{n+1} through output channel 1 as shown in Fig. 2. According to quantum theory, the probability amplitude of photons ending up in path b_0 and b_1 of a beam splitter are given by

$$\begin{pmatrix} b_0 \\ b_1 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix}\begin{pmatrix} a_0 \\ a_1 \end{pmatrix}, \tag{4}$$

Finally, the probability of a photon in path b_0 and b_1 are given by

$$P_{b_0} = |b_0|^2 = \frac{1 + 2\sqrt{p_0(1-p_0)}\sin(\psi_0 - \psi_1)}{2},$$
$$P_{b_1} = |b_1|^2 = \frac{1 - 2\sqrt{p_0(1-p_0)}\sin(\psi_0 - \psi_1)}{2}, \tag{5}$$

2.2. Mach-Zehnder Interferometer

A Mach-Zehnder Interferometer is an experiment that consist of a photon source, two beam splitters, two mirrors, two phase shifters and detectors. The diagram is shown by Fig. 1. MZI simulation is built by combining two DLMs. The probability amplitude of photons ending up in b_2 (detector N_2) and b_3 (detector N_3) are given by

$$\begin{pmatrix} b_2 \\ b_3 \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix}\begin{pmatrix} e^{i\phi_0} & 0 \\ 0 & e^{i\phi_1} \end{pmatrix}\begin{pmatrix} b_0 \\ b_1 \end{pmatrix}, \tag{6}$$

Finally, the number of photon ending in detector N_2 and N_3 are given by

$$N_2 = N|b_2|^2 = N \sin\frac{\phi}{2} \ , \tag{7}$$

$$N_2 = N|b_3|^2 = N \cos\frac{\phi}{2} \ . \tag{8}$$

2.3. MZI with An Absorber

The schematics experiment of MZI has been explained in section 2.2. When the particles ending up in detector N_3, then the wave function can be obtained as follows

$$\psi_{N_3} = \psi_{b_1} + \psi_{b_0} e^{i\phi}, \tag{9}$$

where ψ_{b_0} and ψ_{b_1} are the wave function at path b_0 and b_1, respectively. While ϕ is the phase different. By adding an absorber in path b_1, the number of particles are reduced by the factor of a. a is the probability of particles to pass through the absorber $(0 < a < 1)$. The particles are absorbed when the chopper close, while the particles are passed when the chopper open (see Fig. 1). Hence the detector N_3 reads

$$\psi_{N_3 open} = \psi_{b_1} + \psi_{b_0} e^{i\phi}, \tag{10}$$

In the closed position, the wave function becomes

$$\psi_{N_3 close} = \psi_{b_0} e^{i\phi}, \tag{11}$$

the particles pass through path b_0 only. The final intensity of the dynamic absorber (periodic chopper) is the sum of the squares of the two contributions function (open and close position), weight by a and $(1 - a)$

$$I_{N_3} = a|\psi_{b_1}|^2 + |\psi_{b_0}|^2 + 2a\psi_{b_0}\psi_{b_1} \cos\phi. \tag{12}$$

3. The Methods

The simulation was built by employing the DLM described in section 2.1. The simulation did 100000 events $(N_0 + N_1 = N_2 + N_3)$ with $\alpha = 0.98$. It combined two DLMs, a photon source, two phase shifters, two perfectly reflecting mirrors, detectors and a dynamics absorber (a periodic chopper). The simulation only used particles (photon), not wave. The photon which consider as a messenger was produced by a photon source and carried message. The message was two-dimensional unit vector $y_{k,n} = (\cos\psi_n, \sin\psi_n)$, where ψ_n represented the photon phase, the subscribe n was the label of messenger. The messages were then processed by the DLM. Input channel 0 of DLM received $(\cos\psi_0, \sin\psi_0)$ with probability one and $\psi_0 = 0$, therefore input channel 1 received no messages. Because the message entered input channel 0, then the event was represented by vector $v_n(1,0)$. Initially the rotation angles were $\phi_0 = 0^\circ$ and $\phi_1 = 0^\circ$. After each 100000 events, ϕ_0 was increased by 10°. The periodic chopper was added to path b_1 and replaced the plane rotation $R(\phi_1)$. The probability of particles pass through the absorber are $a = 0$,

$a = 0.25$, $a = 0.50$, $a = 0.75$ and $a = 1$. The value of a influenced the periodic chopper rotation (open and close condition). The particles pass through the absorber in the open condition, otherwise particles are absorbed by the periodic chopper in the close condition.

4. Results and Discussion

The simulation result of Mach-Zehnder Interferometer with no absorber was shown by Fig. 3, while Mach-Zehnder Interferometer with an absorber was shown by Fig. 4. In case of Mach-Zehnder Interferometer with no absorber, the interference was shown by the bullets in Fig. 3.

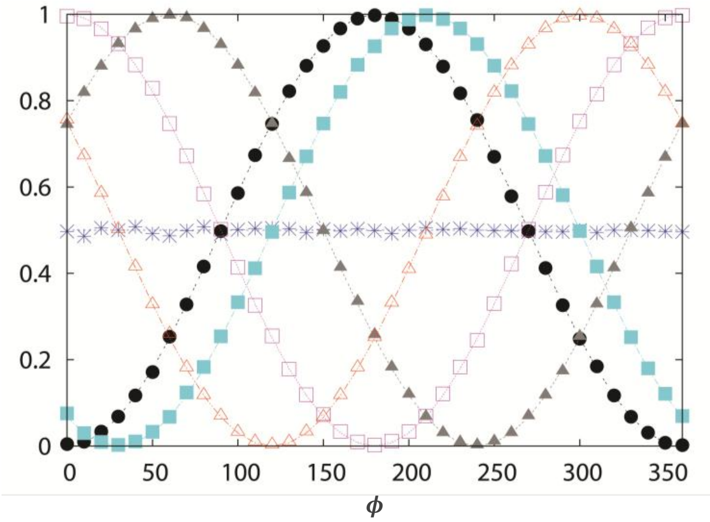

Fig. 3. The simulation result of Mach-Zehnder Interferometer with no absorber. Markers give the simulation results for the normalization of N_3 as the function of ϕ, where $\phi = \phi_0 - \phi_1$. The simulation set $\alpha = 0.98$. The open squares were $N_3/(N_2 + N_3)$ for $\phi_1 = 0^{\circ}$. Lines represent the analytical calculation.

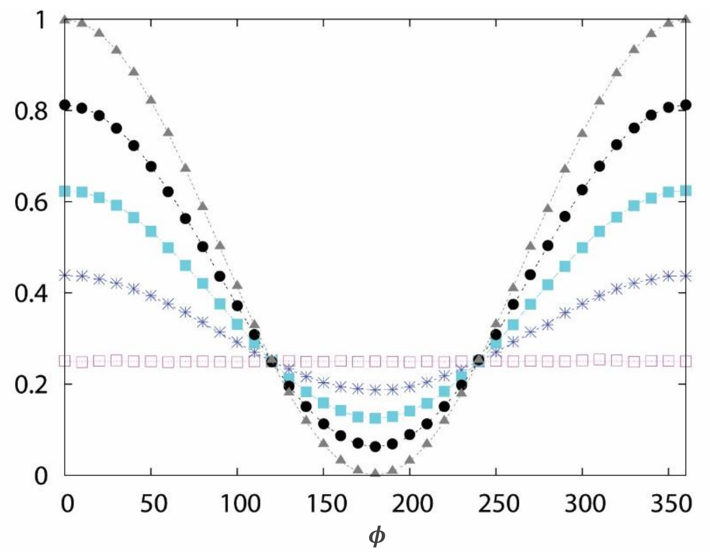

Fig. 4. The simulation result of Mach-Zehnder Interferometer with dynamics absorber. Markers give the simulation results for the normalization of N_3 as the function of ϕ, where $\phi = \phi_0 - \phi_1$. It used $\alpha = 0.98$ and $\phi_1 = 0^{\circ}$. The open squares were $N_3/(N_2 + N_3)$ for $a = 0$, asterisks were $N_3/(N_2 + N_3)$ for $a = 0.25$, squares were $N_3/(N_2 + N_3)$ for $a = 0.50$, bullets were $N_3/(N_2 + N_3)$ for $a = 0.75$, and triangles were $N_3/(N_2 + N_3)$ for $a = 1$. Lines represented the numerical calculation.

In MZI with a dynamic absorber simulation, each data points represent 100000 events ($\boldsymbol{N_0} + \boldsymbol{N_1} = \boldsymbol{N_2} + \boldsymbol{N_3}$). The data points are normalized counts of $\boldsymbol{N_3}/(\boldsymbol{N_2} + \boldsymbol{N_3})$. The simulation shown data of various probabilities of particles to pass through the absorber. At $\boldsymbol{a} = \boldsymbol{1}$ the normalized counts were 1, because all particles passed through the absorber, otherwise at $\boldsymbol{a} = \boldsymbol{0}$ there was no interferences because detector $\boldsymbol{N_3}$ received particles from path $\boldsymbol{b_1}$ only. At $\boldsymbol{a} = \boldsymbol{0.25}$, $\boldsymbol{a} = \boldsymbol{0.5}$, and $\boldsymbol{a} = \boldsymbol{0.75}$ the normalized counted were decreased respectively, because some number of particles passed through the absorber, some others were absorbed.

5. Conclusion

The simulation results produced interference patterns of Mach-Zehnder Interferometer with a dynamic absorber. The simulation results agree with the numerical calculation. It showed wave-particle duality of a particle. The wave-nature was shown by the interferences, while the particle-nature is revealed by the decreasing of interference intensity (normalized counts) as the absorber placed in one of the two beam paths.

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