The Enigma of Delayed Choice Quantum Eraser

Tabish Qureshi

Centre for Theoretical Physics, Jamia Millia Islamia, New Delhi, India. E-mail: tqureshi@jmi.ac.in

Editors: *Stefan K. Kolev & Danko D. Georgiev*

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The delayed-choice quantum eraser represents an interesting experiment that exemplifies Bohr's principle of complementarity in a beautiful way. According to the complementarity principle, in a two-path interference experiment, the knowledge of which path was taken by the particle and the appearance of interference are mutually exclusive. Even when the which-path information is merely retained in specific quantum path-markers, without being actually read, it suffices to eliminate interference. Nevertheless, if this path information is *erased* in some manner, the interference re-emerges, a phenomenon referred to as the quantum eraser. An intriguing aspect of this experiment is that if the path information is erased *after* the particle has been detected on the screen, the interference still reappears, a phenomenon known as the delayed-choice quantum eraser. This observation has led to the interpretation that the particle can be influenced to exhibit characteristics of either a particle or a wave based on a decision made long after it has been registered on the screen. This idea has sparked considerable debate and discussions surrounding retrocausality. This controversy is reviewed here, and a detailed resolution provided.

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1 Introduction

The two-slit interference experiment with quantum particles (*quantons* for short), holds a coveted position in physics. The fact the individual massive particles, which pass through the slits one by one, accumulate to yield an interference pattern on the screen, has intrigued researchers since the birth of quantum mechanics. The interference characterizes the wave nature of the quantons, whereas the knowing that a quanton passed through a particular slit, brings out its particle nature. Niels Bohr proposed that the two natures of quanton are mutually exclusive. In a single experiment, it is possible to observe only one of the two complementary aspects of the quantons. He considered this aspect as a very fundamental feature of quantum physics, and proposed the *complementarity principle* [1]. People believe that the two-slit interference experiment, with the possibility of path detection, captures the mystery of quantum mechanics in a very fundamental way.

Bohr's complementarity principle has stood the test of time, since its early days when Einstein challenged it [2]. It has been tested in various experiments and has also been quantified using certain duality relations [3, 4]. Scully and Drühl [5] proposed an interesting two-slit experiment in the presence of certain quantum path marker. One could read the path markers and force the quantons to pass through one or the other slit. The path marker reading would indicate precisely through which slit the quanton passed. No interference is observed for such quantons whose path information has been extracted. Alternately one could choose to *erase* the path information by reading out those states of the path marker which do

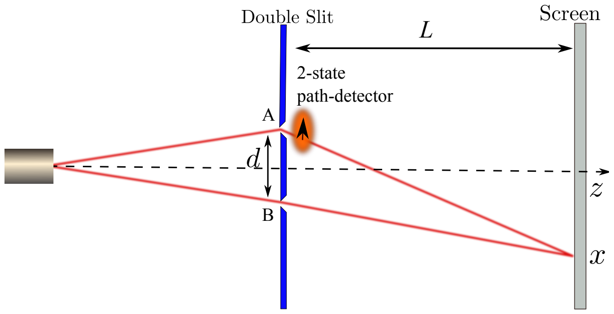

Figure 1: *Schematic diagram of a two-slit interference experiment. There are two possible paths a quanton can take, in arriving at the screen.*

not distinguish between the two paths. They showed that interference re-appears in such a situation. In this way one could choose to make the quantons behave either as particles, or wave. From their analysis they inferred a more dramatic result, namely that one gets the same results even when the path marker is read out after the quanton is detected on the screen. This appears to show that even after the quanton has traversed the double-slit, and is detected on the screen, one can choose to make it behave either like a wave or as a particle. It appears that one can influence the past of the quanton. This experiment generated a huge debate and continues to be discussed both in the scientific and popular literature.

We will first describe the quantum eraser, and how it works, and then discuss the various objections and interpretations. We will then explain how the experiment should be correctly interpreted, and will show that there is no retrocausality involved.

2 The delayed-choice quantum eraser

2.1 The formulation

Consider a two-slit interference experiment as shown in Fig. 1. The quantons emerge from the source, one at a time, pass through the double-slit, and are registered on the screen. The state of the quanton, as it emerges from the double-slit, can be written as

$$|\psi_i\rangle = \frac{1}{\sqrt{2}}(|\psi_A\rangle + |\psi_B\rangle), \quad (1)$$

where $|\psi_A\rangle$ ($|\psi_B\rangle$) represents the state of the quanton if it passes through slit A (B). The quanton travels to the screen, and is registered at a position x on the screen, the probability density of which is given by

$$|\langle x|\psi_f\rangle|^2 = \frac{1}{2}\Big[|\psi_A(x)|^2 + |\psi_B(x)|^2 + \psi_A(x)\psi_B^*(x) + \psi_A^*(x)\psi_B(x)\Big], \quad (2)$$

where $\psi_A(x), \psi_B(x)$ now represent the time evolved wave-functions, $\langle x|\psi_A\rangle, \langle x|\psi_B\rangle$, of the quanton as it travels from the double-slit to the screen. The first two terms represent the probability density if the quanton emerged from slit A or slit B. The last two terms signify the interference between the two amplitudes, resulting in the interference pattern observed in the probability distribution on the screen. This is the basic mechanism of interference in a two-slit experiment.

Let us now introduce a path-detector at the double-slit. Without specifying the nature of the path-detector, we just assume that it is a two-state quantum system. If the quanton passes through slit A (B), the path-detector acquires the state $|d_1\rangle$ ($|d_2\rangle$). The states $|d_1\rangle, |d_2\rangle$ are assumed to be normalized. The combined state of the quanton and the path-detector can now be written as

$$|\psi_i\rangle = \frac{1}{\sqrt{2}}(|\psi_A\rangle|d_1\rangle + |\psi_B\rangle|d_2\rangle). \quad (3)$$

The probability density of the quanton on the screen is now given by

$$|\langle x|\psi_f\rangle|^2 = \frac{1}{2}\Big[|\psi_A(x)|^2 + |\psi_B(x)|^2 + \psi_A(x)\psi_B^*(x)\langle d_2|d_1\rangle + \psi_A^*(x)\psi_B(x)\langle d_1|d_2\rangle\Big], \quad (4)$$

where the interference term is now suppressed by the factor $|\langle d_1|d_2\rangle|$. If $|d_1\rangle, |d_2\rangle$ are orthogonal, the interference term vanishes. By potentially measuring an observable of the path-detector whose eigenstates are $|d_1\rangle, |d_2\rangle$, one can unambiguously tell which slit the quanton passed through. In accordance with the complementarity principle, one would not observe any interference in this situation. On the other hand one could think of another observable of the path-detector whose eigenstates are $|d_\pm\rangle = \frac{1}{\sqrt{2}}(|d_1\rangle \pm |d_2\rangle)$. In terms of these the entangled state (3) can be written as

$$|\psi_i\rangle = \frac{1}{2}(|\psi_A\rangle + |\psi_B\rangle)|d_+\rangle + \frac{1}{2}(|\psi_A\rangle - |\psi_B\rangle)|d_-\rangle. \quad (5)$$

If one looks at only those quantons for which the path-detector state is $|d_+\rangle$, their state is given by

$$|\psi_+\rangle = \frac{1}{\sqrt{2}}(|\psi_A\rangle + |\psi_B\rangle). \quad (6)$$

This state, as we have already seen, gives rise to interference. One the other hand, if one looks at only those quantons for which the path-detector state is $|d_-\rangle$, their state is given by

$$|\psi_-\rangle = \frac{1}{\sqrt{2}}(|\psi_A\rangle - |\psi_B\rangle). \quad (7)$$

This state also gives rise to interference, but the interference pattern will be shifted by a phase difference of π, as

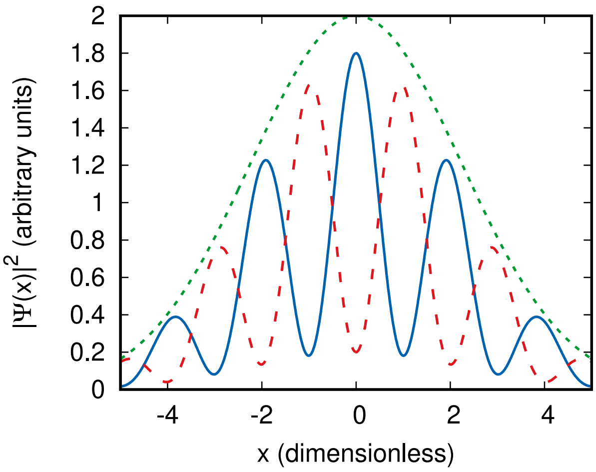

Figure 2: *A typical interference pattern in a two-slit interference in the presence of a which-way detector. The solid line represents the recovered interference corresponding to the path-detector state $|d_+\rangle$, the dashed line represents the recovered interference corresponding to the path-detector state $|d_-\rangle$. If one just detects all the quantons without bothering about the path detector, a washed out interference pattern (the dotted line) is obtained.*

compared to the one corresponding to $\psi_+(x)$. The two, when added together, give no interference. These results are summarized in Fig. 2. The interpretation here is simple – once the path-detector falls into the state $|d_+\rangle$, the potentiality of looking at $|d_1\rangle, |d_2\rangle$ to infer which slit the quanton went through, is lost. In fact, finding the states $|d_\pm\rangle$ implies that the *quanton passed through both the slits*. This again reinforces the complementarity principle in that the appearance of interference implies, no which-path information can be obtained.

Now the joint probability of detecting the quanton at a position x and the path detector in a particular state, does not depend on whether one measures the path detector before or after the quanton hitting the screen. So it appears that one can recover interference by letting the quantons hit the screen first, and considering them only if one gets the state (say) $|d_-\rangle$ in a later measurement. Following the same logic, one might infer that correlating the detected quantons with the states $|d_2\rangle$ or $|d_2\rangle$ will tell us which slit each of them passed through. One would not recover any interference in that situation. This interpretation seems to imply that one could make a quanton pass through a single slit, or both the slits, by a delayed choice. This broadly held view is based on the argument of Englert, Scully and Walther [6, 7] which says that even in the delayed mode, the choice of whether one wants to see $\psi_A(x), \psi_B(x)$ kind of quantons or $\psi_+(x), \psi_-(x)$ kind of quantons, falls to the experimenter. The delayed-choice quantum eraser generated a huge debate which continues to this day [6–20]. Over the years the quantum eraser, with or without delayed-choice, has been realized in different ways [21–32], and several other proposals were made [33–36]. The idea of quantum eraser has also been generalized to three-path interference [37]. Separated from the core issue of quantum eraser, a novel category of delayed-choice experiments featuring a quantum quirk has recently been investigated [38–43]. The objective of these experiments was to examine the potential for a quantum superposition of both wave and particle behaviors.

2.2 Preliminary analysis

It has been pointed out that the delayed-choice quantum eraser experiment is intimately connected to the so-called Einstein–Podolsky–Rosen (EPR) entangled state for two spin-1/2 particles [6, 16, 17]. Consider two spin-1/2 entities in a state

$$|\phi\rangle = \tfrac{1}{\sqrt{2}}(|\uparrow\rangle_1|\uparrow\rangle_2 + |\downarrow\rangle_1|\downarrow\rangle_2), \quad (8)$$

where labels 1 and 2 correspond to the two spins, and the states $|\uparrow\rangle_i$ and $|\downarrow\rangle_i$ represent the eigenstates of the z-component of the spins. It is easy to see the analogy between this state and the state (3). The states corresponding to the two paths, $|\psi_A\rangle, |\psi_B\rangle$ are like eigenstates of the z-component of spin 1, and the path-detector states $|d_1\rangle, |d_2\rangle$ are like the eigenstates of the z-component of spin 2. Just as measuring the z-component of spin 2 can tell one about the z-component of spin 1, looking at $|d_1\rangle, |d_2\rangle$ can tell one which slit the quanton went through. The state (8) can also be represented as

$$|\phi\rangle = \tfrac{1}{\sqrt{2}}(|+\rangle_1|+\rangle_2 + |-\rangle_1|-\rangle_2), \quad (9)$$

where $|\pm\rangle_i$ represent the eigenstates of the x-component of the spins. This state is analogous to the state (5). The states $|\pm\rangle_1$ for spin 1 are like the states $|\psi_\pm\rangle$ of the quanton, which correspond to the quanton passing through both slits. The states $|\pm\rangle_2$ for spin 2 are like the states $|d_\pm\rangle$ of the path-detector. Just as measuring the x-component of spin 2 can tell one about the x-component of spin 1, looking at $|d_\pm\rangle$ can tell one that the quanton went through both the slits, like a wave. The x-component of the two spins are correlated, and so are the z-component of the two spins. Measuring x-component of spin 2 can give no information about the z-component of spin 1. If any third component of spin 1 is measured, that cannot give any information about x- or z-component of spin 2. Measuring any third component of spin 1 first, and then choosing to measure x- or z-component of spin 2 subsequently, to find out what the x- or z-component of spin 1 was, is simply nonsensical. Analogously in the delayed-choice quantum

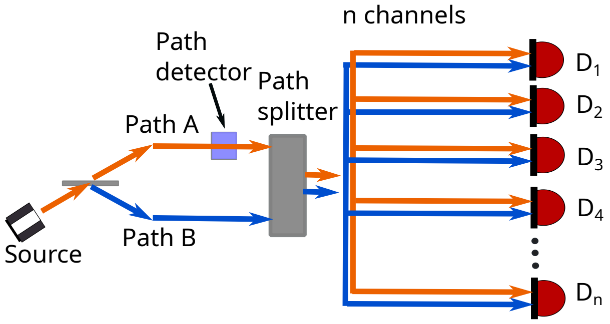

Figure 3: Schematic diagram of a two-path, n−channel interference experiment. There are two possible paths a quanton can take, in arriving at the n output detectors.

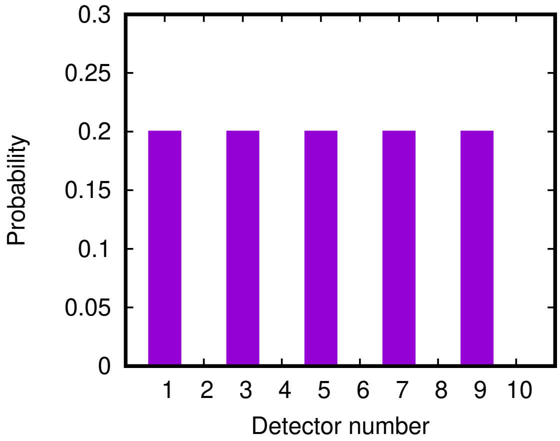

Figure 4: A typical interference pattern for $n = 10$ channels. All the quantons land only at odd numbered detectors, and none at even numbered ones. This represents a fringe pattern.

eraser, if the quanton has already hit the screen, the quanton has been measured in some other basis. Measuring $|d_{1,2}\rangle$ or $|d_\pm\rangle$ subsequently to infer whether the quanton went through a particular slit, or both slits, is also nonsensical. This is the fundamental mistake in the prevalent interpretation of the delayed-choice quantum eraser [6, 7].

3 A n−channel quantum eraser

It has been demonstrated earlier that the delayed-choice quantum eraser can be understood better if one uses a Mach–Zehnder interferometer [44, 45] instead of a two-slit setup [17, 18]. In a Mach–Zehnder interferometer there are two output detectors. The default interference is represented by one particular detector detecting all the quantons, and the other one detecting none. The complementary interference is represented by the other detector registering all the quantons, and the first one detecting none. So path-detector state $|d_+\rangle$ will correspond to all quantons going to the first detector, and $|d_-\rangle$ will correspond to all of them going to the second detector. Here it is obvious that, in the delayed mode, each detector clicking will correspond to either $|d_+\rangle$ or $|d_-\rangle$ state of the path-detector, which means that the quanton followed both the paths, and not just one of the two [17, 18].

In order to make a closer correspondence to the two-slit experiment, here we propose a discrete version of quantum eraser in a more general setting. Consider that the quanton can take two possible paths, and each path is then split into n common channels (see Fig. 3). So a quanton taking path A is equally likely to go to any of the n output channels. The same holds for a quanton taking path B. It is easy to imagine that $n = 2$ corresponds to the Mach–Zehnder interferometer, where each path is split into two output channels. Let us assume that a quanton emitted from the source is split into a superposition of two paths, A and B. The state of the quanton may be written as

$$|\psi_i\rangle = \tfrac{1}{\sqrt{2}}(|\psi_A\rangle + |\psi_B\rangle). \tag{10}$$

Quanton in each path encounters a path-splitter which splits it into a superposition of n channels, each ending in a detector. The action of the path-splitter on the two states can be captured by the effect of a unitary operator $\mathbf{U_{PS}}$ in the following way,

$$\begin{aligned} \mathbf{U_{PS}}|\psi_A\rangle &= \tfrac{1}{\sqrt{n}}\sum_{j=1}^{n} e^{i\theta_j}|D_j\rangle \\ \mathbf{U_{PS}}|\psi_B\rangle &= \tfrac{1}{\sqrt{n}}\sum_{k=1}^{n} e^{i\phi_k}|D_k\rangle, \end{aligned} \tag{11}$$

where θ_m, ϕ_m are the phases picked up by the quanton in arriving at the detector D_m, from paths A and B, respectively. The state of a quanton, when it goes through the m'th channel, and arrives at the detector D_m, is represented by $|D_m\rangle$. Thus the state of a quanton passing through the two paths A and B, and arriving at the final detectors, is given by

$$\begin{aligned} |\psi_f\rangle &= \mathbf{U_{PS}}\tfrac{1}{\sqrt{2}}(|\psi_A\rangle + |\psi_B\rangle) \\ &= \tfrac{1}{\sqrt{2n}}\sum_{j=1}^{n}(e^{i\theta_j} + e^{i\phi_j})|D_j\rangle. \end{aligned} \tag{12}$$

In a simplest case we assume that $\theta_j = 0$ for all j, and $\phi_j = 0$ for odd j's, and $\phi_j = \pi$ for even j's. From (12) one can see that the amplitude for $|D_j\rangle$ will be $\sqrt{2/n}$ for odd j's, and zero for even j's. Consequently all quantons will go to odd numbered detectors, and none to even numbered ones. These correspond to the bright and dark fringes in a two-slit interference experiment (see Fig. 4).

Now in the presence of a path-detector in the path of the quanton, the initial state is

$$|\psi_i\rangle = \tfrac{1}{\sqrt{2}}(|\psi_A\rangle|d_1\rangle + |\psi_B\rangle|d_2\rangle). \tag{13}$$

The final state is then given by

$$|\psi_f\rangle = \mathbf{U_{PS}}\frac{1}{\sqrt{2}}(|\psi_A\rangle|d_1\rangle + |\psi_B\rangle|d_2\rangle)$$
$$= \frac{1}{\sqrt{2n}}\sum_{j=1}^{n}(e^{i\theta_j}|d_1\rangle + e^{i\phi_j}|d_2\rangle)|D_j\rangle. \quad (14)$$

With the phases as before, $\theta_j = 0$ for all j, and $\phi_j = 0$ for odd j's, and $\phi_j = \pi$ for even j's, we find that the probablity of all output detectors registering the quanton is the same, $\frac{1}{2n}\left|e^{i\theta_j}|d_1\rangle + e^{i\phi_j}|d_2\rangle\right|^2 = \frac{1}{n}$. This implies no interference. Now the state (14) can also be written as

$$|\psi_f\rangle = \frac{1}{2\sqrt{n}}\sum_{j=1}^{n}(e^{i\theta_j} + e^{i\phi_j})|d_+\rangle)|D_j\rangle$$
$$+\frac{1}{2\sqrt{n}}\sum_{j=1}^{n}(e^{i\theta_j} - e^{i\phi_j})|d_-\rangle)|D_j\rangle. \quad (15)$$

The quantons, for which the path-detector state is found to be $|d_+\rangle$, will be in the state

$$\langle d_+|\psi_f\rangle = \frac{1}{2\sqrt{n}}\sum_{j=1}^{n}(e^{i\theta_j} + e^{i\phi_j})\langle d_+|d_+\rangle)|D_j\rangle$$
$$+\frac{1}{2\sqrt{n}}\sum_{j=1}^{n}(e^{i\theta_j} - e^{i\phi_j})\langle d_+|d_-\rangle)|D_j\rangle$$
$$= \frac{1}{2\sqrt{n}}\sum_{j=1}^{n}(e^{i\theta_j} + e^{i\phi_j})|D_j\rangle \quad (16)$$

Similarly the quantons, for which the path-detector state is found to be $|d_-\rangle$, will be in the state

$$\langle d_-|\psi_f\rangle = \frac{1}{2\sqrt{n}}\sum_{j=1}^{n}(e^{i\theta_j} - e^{i\phi_j})|D_j\rangle. \quad (17)$$

Considering that $\theta_j = 0$ for all j, and $\phi_j = 0$ for odd j's, and $\phi_j = \pi$ for even j's, it is straightforward to see that the quantons in the state (16) will all land on odd numbered detectors, and the ones in the state (17) will all land on even numbered detectors. The outcome is illustrated in Fig. 5. It can be interpreted as a discrete version of Fig. 2.

What is most interesting in this n−channel quantum eraser is that in the *delayed mode*, every quanton detected at an odd numbered detector will throw the path-detector in a *definite* state $|d_+\rangle$, and every quanton detected at an even numbered detector will throw it in a *definite* state $|d_-\rangle$. And both these path-detector states correspond to the quanton following both the paths, hence behaving like a wave. So in the delayed mode there is no choice for the experimenter. Every registered quanton follows both the paths, and the which-way information is erased. This contradicts the widely held belief [6, 7].

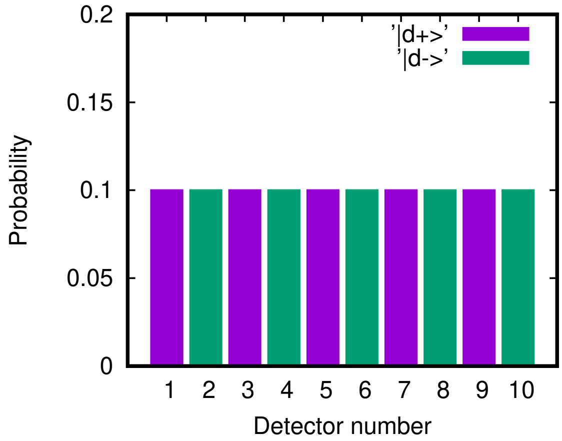

Figure 5: *Recovered interference patterns for $n = 10$ channels, in the presence of a path detector. Corresponding to the path-detector state $|d_+\rangle$ all the quantons land only at odd numbered detectors. Corresponding to the path-detector state $|d_-\rangle$ all the quantons land only at even numbered detectors.*

4 The two-slit quantum eraser

The lingering question is whether we can derive the same conclusion for a two-slit quantum eraser as we did for the n−channel quantum eraser. We will address this question in the present section. The first thing to recognize is that in a two-slit quantum eraser the two complementary interference patters, depicted in Fig. 2, are not the only ones that can be recovered, and $|d_\pm\rangle$ are not the only two path-detector states that can be used for quantum erasing. In fact there exist an infinite number of mutually unbiased basis sets for the path detectors, $|d_\pm^\theta\rangle = \frac{1}{\sqrt{2}}(e^{i\theta}|d_1\rangle \pm e^{-i\theta}|d_2\rangle)$, which can be used for quantum erasing, where θ is an arbitrary phase factor. The recovered interference pattern corresponding to $|d_+^\theta\rangle$ will be shifted as compared to the recovered pattern corresponding to $|d_+\rangle$. However in the delayed mode, as the quanton is registered on the screen first, there is no reason why the states $|d_\pm\rangle$ should emerge on their own.

In order to understand what happens in a two-slit quantum eraser, we approach it in a manner akin to the n−channel quantum eraser examined in the previous discussion. Nevertheless, in this case, the channels (as well as the final detectors) are neither discrete nor finite. Rather the screen represents an infinite number of positions x at which the quanton can arrive. Also, in this case there is no path-splitter that is employed. It is the Schrödinger evolution of the initially localized wave-packet emerging from a slit, which makes it spread over an infinite set of positions at the screen. The path-splitter action depicted by (11) is then modified to a continuous scenario as

$$\mathbf{U_{PS}}|\psi_A\rangle = \int \psi(x)e^{i\theta_x}|x\rangle dx$$

$$\mathbf{U_{PS}}|\psi_B\rangle = \int \psi(x)e^{i\phi_x}|x\rangle dx, \quad (18)$$

where $|x\rangle$ represents a position eigenstate, and $\psi(x)$ is an envelope function which is approximately assumed to be the same for the two states. In the presence of a path-detector, the final state at the screen is given by

$$\begin{aligned} |\psi_f\rangle &= \mathbf{U_{PS}}\tfrac{1}{\sqrt{2}}(|\psi_A\rangle|d_1\rangle + |\psi_B\rangle|d_2\rangle) \\ &= \tfrac{1}{\sqrt{2}}\int \psi(x)(e^{i\theta_x}|d_1\rangle + e^{i\phi_x}|d_2\rangle)|x\rangle dx. \quad (19) \end{aligned}$$

This represents no interference because $|\langle x|\psi_f\rangle|^2 = |\psi(x)|^2$, due to the orthogonality of $|d_1\rangle, |d_2\rangle$. In a two-slit experiment, as shown in Fig. 1, the phases are known to be $\theta_x = \pi x d/\lambda L$ and $\phi_x = -\theta_x = -\pi x d/\lambda L$, where λ is the wavelength associated with the quanton. The above state can then be written as

$$|\psi_f\rangle = \tfrac{1}{\sqrt{2}}\int \psi(x)(e^{i\theta_x}|d_1\rangle + e^{-i\theta_x}|d_2\rangle)|x\rangle dx. \quad (20)$$

Now if we choose a basis, for the path-detector states, given by $|d_\pm^\theta\rangle = \frac{1}{\sqrt{2}}(e^{i\theta}|d_1\rangle + e^{-i\theta}|d_2\rangle$, the above state can be written as

$$\begin{aligned} |\psi_f\rangle &= \tfrac{1}{2}\int \psi(x)(e^{i(\theta_x-\theta)} + e^{-i(\theta_x-\theta)})|d_+^\theta\rangle|x\rangle dx \\ &\quad + \tfrac{1}{2}\int \psi(x)(e^{i(\theta_x-\theta)} - e^{-i(\theta_x-\theta)})|d_-^\theta\rangle|x\rangle dx \\ &= \int \psi(x)\cos(\theta_x-\theta)|d_+^\theta\rangle|x\rangle dx \\ &\quad + \int \psi(x) i\sin(\theta_x-\theta)|d_-^\theta\rangle|x\rangle dx. \quad (21) \end{aligned}$$

Path information can be erased by choosing the path-detector state $|d_+^\theta\rangle$, which yields the probability density of finding the quanton at a position x

$$|\langle x| \otimes \langle d_+^\theta|\psi_f\rangle|^2 = \tfrac{1}{2}|\psi(x)|^2[1 + \cos(\tfrac{2\pi x d}{\lambda L} - 2\theta)] \quad (22)$$

The probability density of quantons coincident with $|d_-^\theta\rangle$ is given by

$$|\langle x| \otimes \langle d_-^\theta|\psi_f\rangle|^2 = \tfrac{1}{2}|\psi(x)|^2[1 - \cos(\tfrac{2\pi x d}{\lambda L} - 2\theta)]. \quad (23)$$

Eqns. (22) and (23) represent two complementary interference patterns similar to those depicted in Fig. 2, but a little shifted if θ is nonzero.

Now we are in a position to understand what happens in the delayed mode. From (21) one can see that when a quanton lands at a position x, both $|d_+^\theta\rangle$ and $|d_-^\theta\rangle$ have nonzero probabilities of occurring. However, if the path-detector basis is chosen such that $\theta = \theta_x$, for that particular position x, the combined state (21) becomes

$$|\psi_f\rangle = \int \psi(x)|d_+^{\theta_x}\rangle|x\rangle dx, \quad (24)$$

which means that the path-detector comes to a *definite* state $|d_+^{\theta_x}\rangle$. This in turns means that the path information is erased, and the quanton followed both paths. For each position x at which a quanton arrives, there is a corresponding basis in which the path detector will be in a definite state. This indicates that even in the two-slit delayed-choice quantum eraser, the quanton always traverses both paths, and the which-path information is always erased. There is no choice left for the experimenter to recover the path information.

5 Discussion

We first analyzed a thought implementation of quantum eraser in a two-path interference experiment where each path is split into n channels. The two amplitudes from the two paths interfere constructively in some channels and destructively in others. This may be interpreted as a discrete version of the conventional two-slit interference experiment. For $n = 2$ it reduces to the Mach–Zehnder interferometer. A path-detector is added to the setup to obtain information on which of the two paths a quanton followed. It is demonstrated that in the delayed mode a quanton landing at an odd (even) numbered detector leaves the path-detector in the state $|d_+\rangle$ ($|d_-\rangle$). Both these states correspond to the quanton following both paths, like a wave. This conclusively shows that in the delayed mode of the quantum eraser, the quanton always follows both the paths, and the which-path information gets erased.

Next we analyzed the conventional two-slit delayed-choice quantum eraser using the same methodology that was used to study the $n-$channel quantum eraser. It is a bit more involved than the $n-$channel quantum eraser because the phase picked up by the quanton in arriving at a position x on the screen is different for each position. Nevertheless, in the delayed mode, every quanton still passes through both the slits, and this information is registered in a *definite* state of the path detector. This path detector state depends on the position where the quanton lands, and is given by $\frac{1}{\sqrt{2}}(e^{i\theta}|d_1\rangle + e^{-i\theta}|d_2\rangle$, where $\theta = \pi x/w$, w being the fringe-width of the two-slit interference $w = \lambda L/d$. This can be verified in an experiment by first locating the precise position of the quanton, inferring the value of θ from that, and then probing the path detector in the basis formed by the states $\frac{1}{\sqrt{2}}(e^{i\theta}|d_1\rangle \pm e^{-i\theta}|d_2\rangle$. Previous authors [6, 16] correctly identified the analogy between the quantum eraser and the an EPR pair of spin-1/2, but missed the point that one needs to consider other mutually unbiased basis sets of the path detector to correctly interpret the experiment.

Finally we would like to mention some important interpretations of the delayed-choice quantum eraser, that our analysis provides.

- If one measures the which-way detector first, one may choose to obtain which-way information, or erase the which-way information by looking at two different sets of basis states.
- If the which-way detector is not measured, the quanton follows both the paths, always.
- In the delayed mode, the which-way information is erased for every quanton, yet the interference is lost. The absence of interference in this context does not imply that any which-way information exists.
- In the delayed mode, for every detected quanton the path detector is left in a definite state. This state informs us not only that the quanton traversed both paths, but it also provides precise information regarding the phase difference between the two paths.
- Nonetheless, the interference pattern, of any specific form selected, can be retrieved in the delayed mode by opting to measure the path detector in the basis pertinent to the selection, and by correlating the registered quantons with various detector states. However, these recovered patterns should not be interpreted as telling us how the quanton traveled the two paths. That information is there in the definite state that the path detector is left in.

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