

# Interaction-Free Which-Path Information and Some of Its Consequences

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Let us consider a single particle in an interferometer. If one of the two possible paths is blocked and the particle is detected, we know that the particle has followed the path which is not blocked. This would be an interference-free “which-path” information experiment. However, we no longer have an interferometer, since one path is blocked. An alternative is to interact with the particle, but this would change its momentum and as a consequence the interference fringes would disappear, as discussed by Feynman. We can also consider two particles entangled in direction. Knowing the path followed by one of the particles, it is possible to know the path followed by the other. On the other hand, when this information is erased, interference can be observed. However, this is a two particle interference: no single particle interference can be observed. Retrodiction experiments are also possible, but these are not conclusive. Here we propose a much less intuitive experiment in which, without blocking one path or directly interacting with the particle, it is possible to know the path which is being followed by the particle in the interferometer. According to quantum mechanics, this is sufficient to lose the single particle interference. The same idea can be used to test the local pilot wave interpretation, to test quantum nonlocality under new conditions, and to devise an interferometer for a two-photon wave packet. This last result strongly suggests that there must be some connection between the deBroglie wavelength of an  $N$ -particle wave packet and entanglement.

**Key words:** Interaction-free Measurement; Pilot-wave Interpretation; Quantum Nonlocality; de Broglie Wavelength of an  $N$ -particle Wave Packet.

## 1. Introduction

Measurements in which reduction of the state vector is apparently produced by the absence of interaction of the system which is being measured with the measurement apparatus have been discussed by Renninger [1] and Dicke [2], and more recently by Elitzur and Vaidman [3], who suggested an interaction-free (IF) way to determine the presence of an object on one arm of an interferometer. Experimental schemes have been proposed to implement their proposal [4], and classical versions of it have been performed [5]. A nonlocal IF test of quantum mechanics has also been suggested [6]. However, so far, no feasible experiments to determine the path followed by a particle in an interferometer without directly interacting with the particle have been devised. Naturally, if one of the two possible paths in a Mach-Zehnder (M-Z) interferometer is blocked and the particle is detected, we know that the particle has followed the path which is not blocked. Although this might be considered an interaction-free which-path information (IFWPI) experiment

(in its most trivial version), we no longer have an interferometer, since one of the two paths is blocked. Another possibility would be to interact with the particle. This would change its momentum and as a consequence make the interference fringes disappear [7]. Naturally, this cannot be considered an IF experiment, but it can give us some insight into how to make an authentic IFWPI experiment, as I will show below. We may also consider particles entangled in direction, such as a pair of photons generated via spontaneous parametric down-conversion (SPCD). Knowing the path followed by one of the particles, we immediately know the path followed by the other. When this information is erased, two-photon interference can be observed [8]. However, single particle interference never occurs, with or without path information. Some retrodiction experiments, based on interference phenomena, in which one infers the path which has been followed by the particle, are also interesting, but not conclusive, since, strictly speaking, there is no such thing as “the *real* path followed by a particle.” All we have are probability amplitudes. On the other hand,

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if we adopt the pilot wave interpretation, these experiments give us information only about the path which has been followed by the wave, not by the particle. Which-path information experiments are only meaningful when they allow us, *at least in principle*, to determine the path which is being followed by the particle; that is, we know where to detect it if we decide to do so. Retrodiction, when applied to two-photon interference, can lead to conflicting pictures [9]. Here I wish to discuss a much less intuitive experiment in which, without blocking one path or directly interacting with the particle, it is possible to know the path which it is following. Naturally, we will lose the single particle interference we should have in case no information about the path had been obtained. This is one of the most amazing consequences of the quantum mechanical formalism. The same idea can be used to envisage a test of the local pilot wave interpretation, to test quantum nonlocality under new conditions, and to devise an M-Z interferometer for two, and even three photons.

Feynman, when discussing the two-slit experiment [7], imagined a very strong light source placed behind the screen with the two slits. The scattering of light by the particle would indicate the slit the particle had passed. However, we can imagine a slightly modified experiment in which we have a very carefully collimated beam of light passing behind only one of the slits. If the probability of a photon being scattered whenever a particle goes through the illuminated slit is close to one, and if the probability of this scattered photon being registered is also close to one, each time a particle is detected and *no* photon is registered, we infer that the particle has passed through the “dark” slit. This would be a satisfactory IFWPI experiment, but one not easy to do. Here I will show how an equivalent experiment can be performed using an M-Z interferometer.

## 2. Interaction-free Which-path Information

Let us consider the interferometer represented in Fig. 1, in which  $H_1$ ,  $H_2$ ,  $H_3$ , and  $H_4$  are 50:50 beam splitters (B. S.). A photon (which can be generated via SPDC, for example) impinges on  $H_1$ . In our experiment another photon will impinge on  $H_2$ , but let us initially consider the situation in which we have only the first photon. If we take into account only the detections at sites 4 and 5, we know that  $P_4 = \frac{1}{2}(1 + \cos \phi)$  and  $P_5 = \frac{1}{2}(1 - \cos \phi)$ , where  $\phi$  is a phase shift. Let us now introduce the second photon, which is an “identical twin” of the first one,

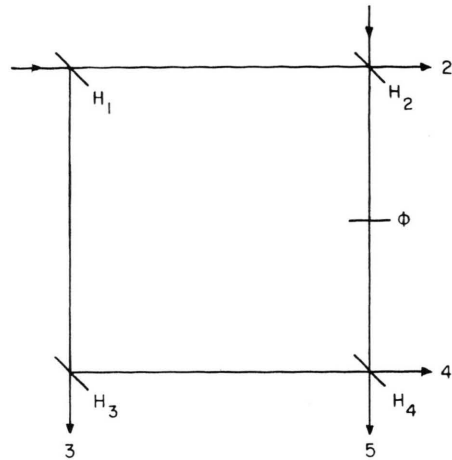


Fig. 1. Experiment to obtain interaction-free which-path information (IFWPI).

and can be generated in a type-I degenerate SPDC process, for example, or in another crystal, also via SPDC, using pulsed lasers [10]. The experiment is devised so that, if the first photon is transmitted at  $H_1$ , it arrives together with the second photon at  $H_2$ . We know, from the properties of bosons and from the experiment by Hong, Ou, and Mandel [11], that after  $H_2$  the two photons have to follow the same direction. Therefore, if one photon is detected at site 2 and the other at site 4 or at site 5, which can be checked using a coincidence circuit, we know that the first photon has followed the path with B. S.s  $H_1$ ,  $H_3$ , and  $H_4$ . In this case,  $P_4 = P_5 = 1/2$ , no interference occurs. In principle, to verify that the detection at site 2 gives us information about the path followed by the first photon, we can remove  $H_4$  while the first photon is still in the interferometer, as in a delayed-choice experiment. Detecting only one photon at site 2 is equivalent to registering no scattered photon in the modified two-slit experiment. The absence of “interaction” (or bosonic behavior, strictly speaking) gives us information about the path followed by the other photon. It is easy to see, using the quantum mechanical formalism, that the interference is lost.

## 3. Testing the Pilot-wave Interpretation

According to the pilot wave interpretation (PWI), whenever a photon impinges on a B. S., is split into two different waves: a “full” wave, which contains the photon, and an “empty” wave [12]. The photon is “guided”

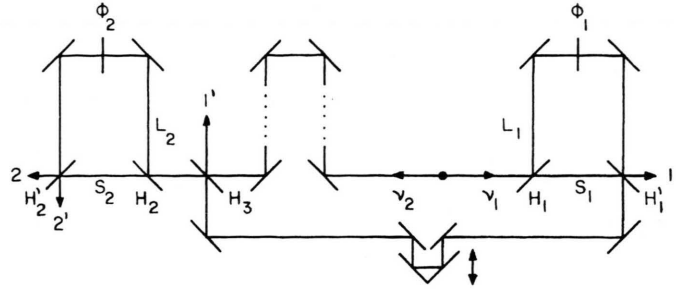
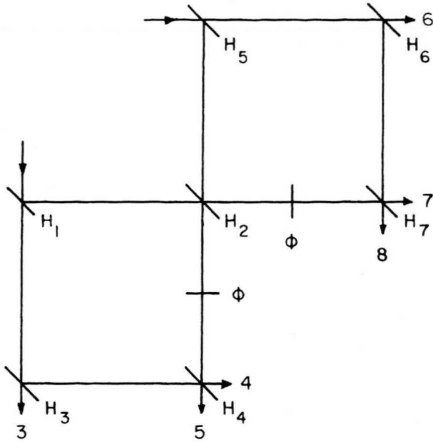


Fig. 3. A variant of Franson's two-photon interference experiment, in which it is possible to obtain IFWPI.

◀ Fig. 2. Experiment to test the pilot wave interpretation.

by the wave. So, in this interpretation it is possible to picture in a more intuitive way the particle-like and wave-like behaviors of light. The experiment represented in Fig. 2, which is based on the experiment represented in Fig. 1, allows us to test the PWI. We are only interested in the situations in which coincident detections occur either at 4 and 7, at 4 and 8, at 5 and 7, or at 5 and 8.  $\phi$  is chosen such that whenever there is one photon impinging on  $H_1$  ( $H_5$ ) and no photon impinging on  $H_5$  ( $H_1$ ) no detection occurs at site 4 (8). Whenever one photon impinges on  $H_1$  and another on  $H_5$ , and  $H_4$  ( $H_7$ ) is removed, a detection at site 4 (8) gives us no information about the path followed by the other photon; as a consequence, no detection can occur at 8 (4). On the other hand, detection of a single photon at site 5 (7) allows us to infer that the other photon has followed the path with the B. S.  $H_6$  ( $H_3$ ). Therefore, considering the situation with the two photons and with the B. S.s in place, whenever a single photon is detected at site 4 (8), it is possible to infer that the other photon has followed the path with the B. S.  $H_2$ . As a consequence, according to the PWI, there can be no coincident detection at sites 4 and 8, since the two photons would have to arrive together at the B. S.  $H_2$  and would necessarily follow the same direction. On the other hand, according to quantum mechanics, there can be coincident detection, since the detection at site 4 (8) gives us information about the path followed by the other photon; as a consequence, there are equal probabilities of it being detected at sites 7 (4) or 8 (5). It is worth noticing that, if in the experiment represented in Fig. 1 an extra B. S. is introduced into the path of the second photon before it impinges on  $H_2$ , there is a possibility of it being reflected into another direction. Whenever it is detected in this direction, no infor-

mation about the path followed by the first photon is obtained; as a consequence, single photon interference will be observed. That is, the empty wave of the second photon cannot guide the first.

#### 4. Testing Quantum Nonlocality under New Conditions

The experiment represented in Fig. 3 is a variant of Franson's two-photon interference experiment [13], based on the IFWPI experiment. The path followed by photon  $\nu_2$  to impinge on  $H_2$  is longer than the path followed by photon  $\nu_1$  to impinge on  $H_1$ . When the B. S.  $H_3$  is not in place, it is impossible to distinguish the situation in which both photons follow the short paths,  $S_1$  and  $S_2$ , from the situation in which both follow the long paths,  $L_1$  and  $L_2$ . I will refer to the corresponding detections as "coincident". The paths are initially chosen such that, when  $H_3$  is in place and  $\nu_1$  follows path  $L_1$ ,  $\nu_1$  and  $\nu_2$  arrive together at  $H_3$ . We are assuming that the two photons are identical. So, when  $H_3$  is in place, any coincident detection occurring at sites 1' and 2 (or 2') makes it possible to infer that both photons have followed the short paths, which leads to the destruction of interference. If they had followed the long paths they would have had to follow the same direction after  $H_3$ , and no coincident detection at 1' and 2 (or 2') would have occurred. A "trombone" is used to change the distance followed by  $\nu_1$  from  $H_1'$  to  $H_3$ . When the distance is chosen such that  $\nu_1$  and  $\nu_2$  arrive together at  $H_3$  only when  $\nu_1$  follows path  $S_1$ , no interference can be observed again, but for intermediary positions of the trombone the interference must reappear.

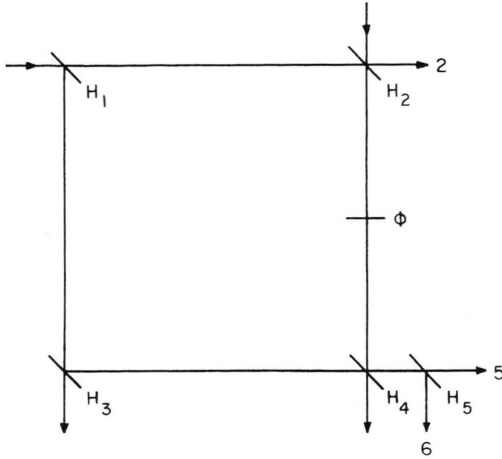


Fig. 4. A Mach-Zehnder interferometer for a two-photon wave packet.

### 5. A Mach-Zehnder Interferometer for a Two-Photon Wave Packet

The experiment represented in Fig. 4, being proposed by myself and Paulo Ribeiro, also from the Institute of Physics of the Federal University of Rio de Janeiro, shows how to construct an interferometer for a two-photon wave packet. Now we have two photons impinging on  $H_1$  and a third photon impinging on  $H_2$ . We use a triple coincidence circuit to register the detections at sites 2, 5, and 6. The experiment is devised so that, if only one photon is transmitted at  $H_1$  it will arrive together with the third photon at  $H_2$ . In this case, the two photons will follow the same direction and no triple coincidence will be registered. Therefore, whenever only a single photon is detected at site 2, we are allowed to infer that either the two photons have been transmitted at  $H_1$  or have been reflected. In this way it is possible to select only those events in which two photons follow the same path together. It is then possible to show that they behave as a single entity with a de Broglie wavelength given by  $\lambda/2$ , where  $\lambda$  is the wavelength of a single photon [14]. In our article we show that this behavior is actually a manifestation of quantum nonlocality [15]. We also show how to build an interferometer for a three-photon wave packet. In this case, the three photons are in a Greenberger-Horne-Zeilinger (GHZ) state [16].

### 6. Entanglement and the de Broglie Wavelength of an $N$ -particle Wave Packet

The previous result strongly suggests that there must be some connection between the de Broglie wavelength of an  $N$ -particle wave packet and entanglement. That this is indeed the case can easily be seen in the situation in which the absolute value of the internal energy of the system of particles is much smaller than the energy associated with the rest masses of the particles. In this case, the rest mass of the  $N$ -particle system is simply the sum of the rest masses of the individual particles. Thus,

$$\frac{h}{\lambda} = p = \gamma v \sum m_j = \sum \gamma m_j v = \sum p_j = \sum \frac{h}{\lambda_j}, \quad (1)$$

which leads to

$$\frac{1}{\lambda} = \sum \frac{1}{\lambda_j}. \quad (2)$$

That is, the reciprocal of the de Broglie wavelength associated with the  $N$ -particles wave packet as a whole is equal to the sum of the reciprocals of the de Broglie wavelengths associated with each individual particle, assuming that the velocity of each particle is equal to the velocity of the  $N$ -particle system as a whole. On the other hand, for our purposes, the initial  $N$ -particle state can be represented as  $|1\rangle|2\rangle\ldots|N\rangle$ , where  $|j\rangle$  ( $j = 1, 2, \dots, N$ ) represents the ket associated with the  $j^{\text{th}}$  particle. After impinging on a beam splitter which acts on the  $N$ -particle system as a whole, the  $N$ -particle state is given by

$$\frac{1}{\sqrt{2}} (|1, a\rangle|2, a\rangle\ldots|N, a\rangle + |1, b\rangle|1, b\rangle\ldots|N, b\rangle), \quad (3)$$

where  $|j, a\rangle$  ( $|j, b\rangle$ ), represents particle  $j$  following path  $a$  ( $b$ ). Now we have a direction-entangled state. If a phase shifter is introduced on path  $a$ , state (3) changes to

$$\frac{1}{\sqrt{2}} [e^{i(\phi_1 + \phi_2 + \dots + \phi_N)} |1, a\rangle|2, a\rangle\ldots|N, a\rangle + |1, b\rangle|1, b\rangle\ldots|N, b\rangle], \quad (4)$$

where  $\phi_j = 2\pi\delta l/\lambda_j$  and  $\delta l$  is a small difference between the two path lengths in the interferometer. The overall phase introduced is

$$\phi = \sum \phi_j, \quad (5)$$

which leads to

$$2\pi \frac{\delta l}{\lambda} = \sum 2\pi \frac{\delta l}{\lambda_j} \quad (6)$$

and to result (2).

State (3) is a GHZ state, connected to quantum mechanical nonlocality. From this point of view, and based on our derivation of the relation between  $\lambda$  and  $\lambda_j$ , we can say that, in a certain sense, the de Broglie wavelength of an  $N$ -particle wave packet is a local manifestation of quantum mechanical nonlocality.

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