Scientific Research Publishing

Journal of Quantum Information Science, 2021, 11, 125-134
https://www.scirp.org/journal/jqis
ISSN Online: 2162-576X
ISSN Print: 2162-5751

What Was in the Apparatus before the Click of the Detector?

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How to cite this paper: Wechsler, S.D. (2021) What Was in the Apparatus before the Click of the Detector? *Journal of Quantum Information Science*, **11**, 125-134.
https://doi.org/10.4236/jqis.2021.114010

Received: September 1, 2021
Accepted: November 1, 2021
Published: November 4, 2021

Abstract

When a quantum system is described by a superposition of wave-packets, each wave-packet traveling on a separate path, a commonly asked question is *why* only one of the wave-packets is able to trigger a click in a detector. In the second half of the last century many scientists considered the possibility that not all these wave-packets are identical. Namely, that there exist "full waves" and "empty waves". The two types of waves were supposed to be identical only in the sense that they are able to produce interference when crossing one another, however, the full wave was supposed to be able to trigger a click in a detector, while the empty wave was supposed to leave the detector silent. The present text describes an experiment in which, for explaining the results, it seems necessary to admit the existence of full and empty waves.

Keywords

Two-Particle Interference, Coherence Length, Full Waves, Empty Waves

1. Introduction

Although the quantum mechanics (QM) succeeded to explain a wide range of phenomena of the microscopic world, for almost a century the most basic features of a quantum systems are still not clarified. How does look like this system? What is the wave-function (w-f), some real wave traveling in our apparatus, or just a mathematical tool for predicting probabilities? In the latter case, how looks like the "thing" that travels in our apparatus?

A very puzzling property of the quantum systems is the quantum superposition. When the w-f consists in a couple of wave-packets traveling in different regions of the space, "which-way" experiments show that only one of the wave-packets (w-ps) is able to trigger a detector. It seems therefore that only one of the w-ps exists in reality. But this is a false impression. If instead of placing detectors on the paths of the w-ps, the w-ps are deflected and brought to intersect one another, in the intersection region appear interference fringes. This is evidence that both the intersecting w-ps exist in reality. *Then, why only one of them impresses a detector?*

An appealing answer would be that the w-ps differ in their possibility to cause a detection: one of the w-ps possesses this possibility and is usually called in the literature "full wave" while all the other w-ps are "empty waves", *i.e.* do not have this possibility. In the end of the last century the physicists embarked in a wide debate around these matters [1]-[15]. Historically, the terms "empty wave" and "full wave" came from the idea that in the microscopic world there exists a substructure element, not appearing in the QM formalism, an entity floating inside the w-f. Outside the volume occupied by that entity, the w-f was supposed to be "empty" *i.e.* of no effect on the detector.[1]

The best elaborated expression of this idea was the de Broglie-Bohm (dBB) interpretation of the QM, [1] [2] [3]. This interpretation is based on the assumption that there exists a "particle" inside the w-f, and the particle travels along a continuous trajectory together with the w-f and inside it. If the w-f consists of several w-ps, the particle travels with one of them, and the rest of the w-ps are considered some sort of really existing waves, though to which the detectors are insensitive. However, a strong argument was brought against the dBB mechanics in [18].[2]

What was challenged in [18] wasn't the existence of a particle as a substructure of the QM formalism. The possibility of a continuous trajectory for the alleged particle was proved incompatible with the QM predictions. The proof can be immediately generalized for ruling out continuous trajectories for full waves. Still, in [18] the door is left open for assuming the existence of a particle that jumps between the w-ps. Such an interpretation of the QM was proposed by S. Gao, namely that there exists a particle in random, discontinuous motion (RDM) [19] [20] [21]. Regrettably, the random motion is incompatible with the correlations in entanglements. A problem appears if one takes into account that experimenters have *free will* and can choose, independently of one another, at which time to measure the particles and which type of test to perform. An analysis of the RDM interpretation, of its advantages and weaknesses, was done in [22].

The rest of the article has the following line: in the second section an experiment is described, and the results are examined in section 3. The section 4 analyses two particular cases of the experiment in the light of the idea of full and

[1]The idea of two types of waves may remind to the reader the transactional interpretation of the QM, due to J.G. Cramer [16] [17], in which two waves were assumed to determine the measurement result. One wave was assumed to propagate from the source to the detectors forward in time, and the other wave was assumed to propagate backward in time from the detectors to the source. In the hypothesis of full and empty waves, nothing propagates backward in time.

[2]The general line of the proof in [18] is that from a source of particles there are three paths on which the particle may go. It is proved that the particle should have taken at once two of these paths. However, if a particle follows a continuous trajectory between source and detector, it may travel only on one path. Bohm's interpretation of the QM is based on the assumption of continuous trajectories.

empty waves, and finds that this idea offers a very plausible explanation. The section 5 contains conclusions.

2. An Experiment with Down-Conversion Pairs of Photons

A beam of UV photons emitted by a laser, is split by a 50% - 50% beam-splitter BS, Figure 1. There result a transmitted beam, $|1_p\rangle$, and a reflected beam $|1_{p'}\rangle$. These beams land on two identical non-linear crystals, X and $\mathbf{X}'$ respectively. In each crystal, a tiny fraction, $|\alpha|^2$, from the incident UV beam, undergoes down-conversion (DC) to signal-idler (s-i) pairs,

$$|1_p,0,0\rangle \to \beta|1_c,0,0\rangle + \alpha|0,1_s,1_i\rangle, \tag{1}$$

$$|1_{p'},0,0\rangle \to \beta|1_{c'},0,0\rangle + \alpha|0,1_{s'},1_{i'}\rangle, \tag{2}$$

with $|\beta|^2 + |\alpha|^2 = 1$. The notation $|l,m,n\rangle$ describes the state of l UV-photons, m signal-photons and n idler-photons. Each s-i pair exits the crystal in the form of two intersecting cones—Figure 2. From these cones, the screens E and E' select by two small holes in each screen, thin fascicles, one with the signal photon and one with the idler photon. The down-conversion effect has a very small probability. Besides that, the intensity of the laser beam is adjusted so as to have only one signal-idler pair in the apparatus in a given trial of the experiment, and the duration of a trial should be longer than the pair coherence time [23].

Experiment I) Behind the screens E and E' are placed pairs of detectors, S, I, and S', I', respectively—Figure 1. The detectors are considered ideal. We will denote by η^2 the transmission coefficient of the two screens. Thus, the probabilities of pair detection are

$$P_{\mathrm{S,I}} = P_{\mathrm{S',I'}} = \frac{1}{2}|\alpha|^2|\eta|^2. \tag{3}$$

The total probability of detection of a s-i pair is

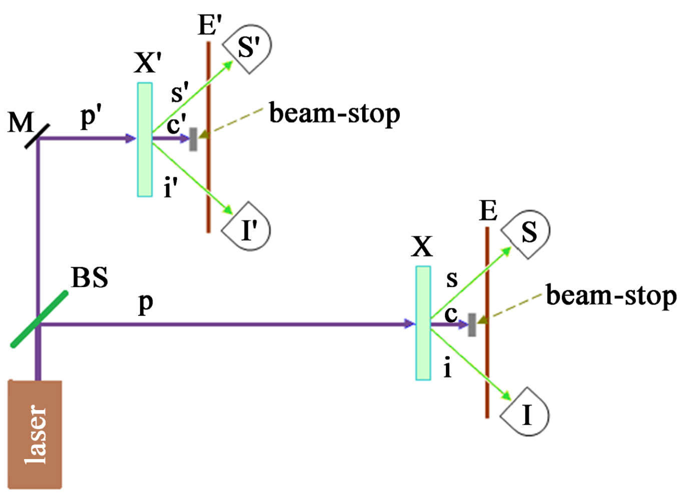

Figure 1. DC-pair production in two non-linear crystals. See explanations in the text.

$$P^0_{\text{detection}} = |\alpha|^2 |\eta|^2 . \tag{4}$$

The meaning of the superscript “0” is the s-i pairs emitted by the two crystals are recorded separately.

Experiment II) The detectors S', I', from the Figure 1 are removed, and the laser is relocated, Figure 3. The signal photon and the idler photon from the screen E' are deflected by mirrors M so as to cross one another on the surface of the crystal X, in the place where the beam $|1_p\rangle$ lands on the crystal. The mirrors M are positioned in such a way that the optical path between the two crystals is equal for the beams $|1_{s'}\rangle$ and $|1_{i'}\rangle$. The laser and the mirrors are positioned such that the path length from the beam-splitter BS to the crystal X along the beam $|1_p\rangle$, is the same as along the beam $|1_{p'}\rangle$ and $|1_{s'}\rangle$ (or $|1_{p'}\rangle$ and

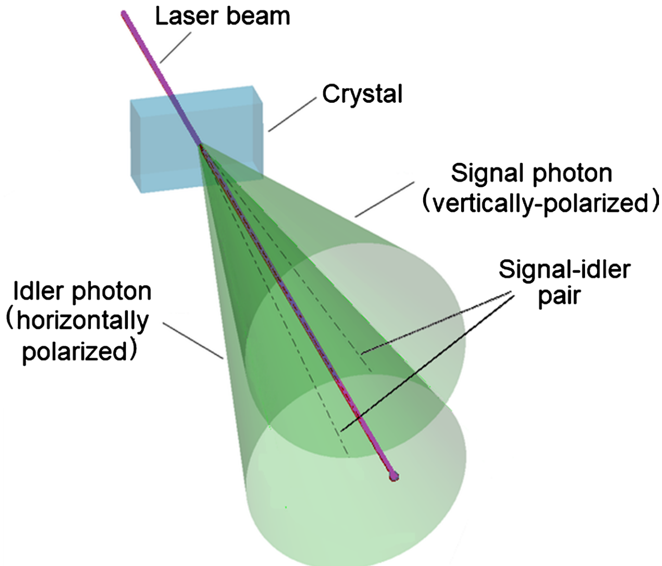

Figure 2. Down-conversion emission.
A typical tableau of down-conversion pairs, the signal and the idler photon belonging to the surface of different cones.

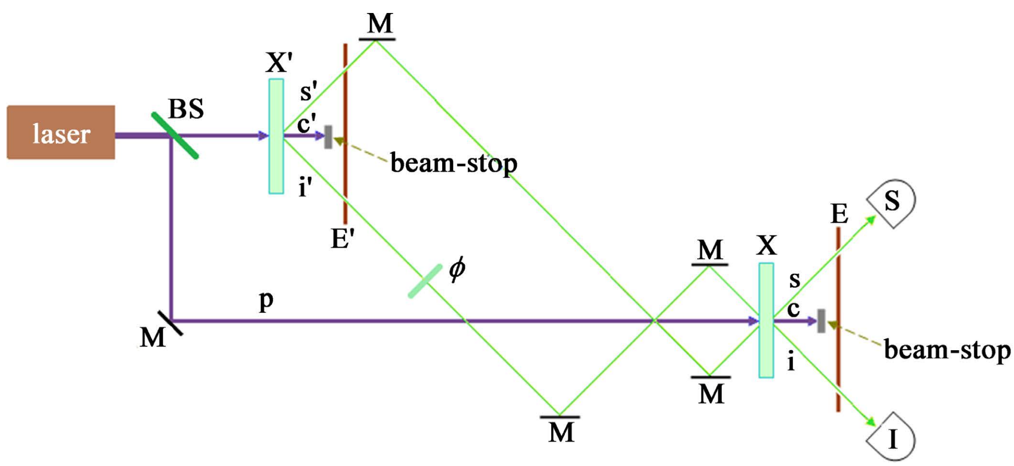

Figure 3. Bringing the paths of the DC-photons from two crystals to overlap.
See explanations in the text.

$|1_{i'}\rangle$). Thus, the s-i wave $|1_{s'},1_{i'}\rangle$ and the pair $|1_s,1_i\rangle$ born in the crystal X, are in phase. The only difference of phase between the two is caused by a phase-shifter by ϕ placed on the path of i'. It will be shown below that this phase-shift controls the yield of pairs from the crystal X.

The experiment is similar with the experiment performed by Herzog *et al.*, [24], however the purposes are different. While the experiment in [24] had the purpose of showing that the two-particle interference can increase or decrease the number of two-photon pairs detected in the detectors S and I, as shown further in section 3, the purpose here is to use this effect for investigating the idea of full and empty waves.

The state of the system of photons on the input side of X is, according to (1) and (2)

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left\{\beta|1_{c'},0,0\rangle + \alpha\eta e^{i\left[2\pi\left(l_{p'}+l_{s'}+l_{i'}\right)/\lambda+\phi\right]}|0,1_{s'},1_{i'}\rangle + e^{i2\pi l_p/\lambda}|1_p,0_s,0_i\rangle\right\},^{3} \quad (5)$$

where $l_{p'}$, l_p, $l_{s'}$, and $l_{i'}$ are, respectively, the path-length of the beam $|1_{p'}\rangle$ from BS to X', of the beam $|1_p\rangle$ from BS to X, of the signal $|1_{s'}\rangle$ and of the idler $|1_{i'}\rangle$ from X' to X. We will denote

$$l_{p'} + l_{s'} + l_{i'} = L'. \quad (6)$$

The UV photon $|1_p\rangle$ produces in the crystal X an s-i pair in the form of intersecting cones, the same as happens beyond the crystal X'—**Figure 2** and transformation (1)—so, the w-f (5) becomes

$$\begin{aligned}|\Psi\rangle = \frac{1}{\sqrt{2}}\Big\{&\beta|1_{c'},0,0\rangle + \alpha\eta e^{i(2\pi L'/\lambda+\phi)}|0,1_{s'},1_{i'}\rangle \\ &+ e^{i2\pi l_p/\lambda}\left(\beta|1_c,0_s,0_i\rangle + \alpha|0_c,1_s,1_i\rangle\right)\Big\}.\end{aligned} \quad (7)$$

From these cones the screen E cuts two fascicles, so the w-f (7) is truncated to

$$\begin{aligned}|\Psi_1\rangle = \frac{1}{\sqrt{2}}\Big\{&\beta\left(e^{i2\pi l_{p'}/\lambda}|1_{c'},0,0\rangle + e^{i2\pi l_p/\lambda}|1_c,0_s,0_i\rangle\right) \\ &+ \alpha\eta\left[e^{i(2\pi L'/\lambda+\phi)}|0,1_{s'},1_{i'}\rangle + e^{i2\pi l_p/\lambda}|0_c,1_s,1_i\rangle\right]\Big\}.\end{aligned} \quad (8)$$

The two-particle wave (2-wave) $|1_{s'},1_{i'}\rangle$ incident to X is partially up-converted in X to UV photons. The rest of this wave passes the crystal unperturbed, however the screen E cuts off the tails of the two fascicles. Let ξ be the up-conversion amplitude and $1/\gamma$ the reduction in amplitude of this 2-wave by the screen E, i.e.

$$|0,1_{s'},1_{i'}\rangle \xrightarrow[X]{} \xi|1_c,0_s,0_i\rangle + \gamma\sqrt{1-|\xi|^2}\,|0_c,1_s,1_i\rangle. \quad (9)$$

Introducing this change in (8) and re-arranging terms, one gets

$$\begin{aligned}|\Psi_2\rangle = \frac{1}{\sqrt{2}}\Big\{&\alpha\eta\left[\gamma\sqrt{1-|\xi|^2}e^{i(2\pi L'/\lambda+\phi)} + e^{i2\pi l_p/\lambda}\right]|0_c,1_s,1_i\rangle \\ &+ \beta|1_{c'},0,0\rangle + \left[\alpha\eta\xi e^{i(2\pi L'/\lambda+\phi)} + e^{i2\pi l_p/\lambda}\beta\right]|1_c,0_s,0_i\rangle\Big\}.\end{aligned} \quad (10)$$

[3]The change in phase by π/2 at each mirror amounts to a total additional phase by 2π on the way of the s-I pair from X', so that it is not mentioned.

We are interested here only in what impinges on the detectors S and I, which appears on the upper line,

$$|\Phi\rangle = \frac{1}{\sqrt{2}}\alpha\eta\left[\gamma\sqrt{1-\xi^2}\,\mathrm{e}^{\mathrm{i}(2\pi L'/\lambda+\phi)} + \mathrm{e}^{\mathrm{i}2\pi l_p/\lambda}\right]|0_c, 1_s, 1_i\rangle. \quad (11)$$

3. The Enhanced and the Inhibited Emission of Pairs

In writing the expression on the RHS of (11) the fact was taken into account that beyond the screen E, nothing reminds the origin of the pair, *i.e.* whether it was born in the crystal X', or in the crystal X. In consequence, two-particle interference occurs between these two 2-waves.

Let's make the coarse approximation,

$$\xi = 0, \gamma = 1, \quad (12)$$

see (9), *i.e.* the wave $|1_{s'}, 1_{i'}\rangle$ passes through the crystal X and the screen E as is. Then, (11) becomes

$$|\Phi\rangle = \frac{1}{\sqrt{2}}\alpha\eta\,\mathrm{e}^{\mathrm{i}2\pi l_p/\lambda}\left[\mathrm{e}^{\mathrm{i}\left[2\pi\left(L'-l_p\right)/\lambda+\phi\right]}+1\right]|0_c, 1_s, 1_i\rangle. \quad (13)$$

Two cases are particularly interesting:

A)

$$\phi = -2\pi\left(L'-l_p\right)/\lambda + 2n\pi. \quad (14)$$

where n is an integer number. From the RHS of (13) results

$$P^{+}_{\mathrm{detection}} = 2|\alpha|^2|\eta|^2. \quad (15)$$

The meaning of the upper script "+", is *enhanced yield of pairs*, twice more than in the case when the pairs $|1_{s'}, 1_{i'}\rangle$ and the pairs $|1_s, 1_i\rangle$ were detected separately, $P^{0}_{\mathrm{detection}}$. Since, the yield from the crystal X' is the same as in the experiment **I**, it means that the crystal X produces thrice as many pairs as in the experiment **I**.

B)

$$\phi = (2n+1)\pi - 2\pi\left(L'-l_p\right)/\lambda. \quad (16)$$

where n is an integer number. From the RHS of (13) there results

$$P^{-}_{\mathrm{detection}} = 0. \quad (17)$$

The meaning of the upper script "–" is *inhibition of pair-production*. As one can see at an examination of the w-f (11), the inhibition is caused by the fact that the fascicles of photons coming from the screen E' interfere destructively with the content of the cones from X within these fascicles.

4. The Full/Empty Waves Hypothesis

In this section are examined the two cases presented above, under the assumption of full and empty waves.

Let's notice that passing from the configuration in the **Figure 1** to that in the

Figure 3 is not a reason for a change in the production of pairs by the crystal X' and in the transmission probability by the screen E' Therefore, within the approximations (12), the probability that a pair originating in X' reach and impress the detectors S and I, remains $P_{S',I'} = \frac{1}{2} P^{0}_{\text{detection}}$. As said in the introduction of the section 2, the apparatus is tuned so that no more than one s-i pair is detected in a single trial of the experiment **I**. Then, if we discard the trials ending with no detection, $P^{0}_{\text{detection}}$ is approximately equal to 1. Therefore, since in passing from the configuration in the Figure 1 to that in the Figure 3 $P_{S',I'}$ remains the same, in two consecutive trials of the experiment **II**, on average, one of the pairs detected by S and I was born in the crystal X', Figure 4.

Now we examine the case **A**.

As shown by (15), the detection probability $P^{+}_{\text{detection}}$ is twice greater than $P^{0}_{\text{detection}}$, *i.e.*, on average, two pairs are detected per trial instead of one, and the extra-pair is generated in the crystal X. Let's examine the process of generation of the extra-pair.

After an s-i pair is detected by the detectors S and I, it leaves the crystal X. So, if the pair came from X', after reaching the detectors it is no more present in the crystal.

Though, the generation of the additional pair per trial is conditioned by the fulfilling of the phase condition (14). This condition needs the presence of the 2-wave from X' because it is a condition between the phase of the 2-wave coming from X' and the phase of the 2-wave born in X. According to the QM, the time at which an s-i pair is born in a crystal is not known. However, whichever would be this time, in one of two trials, on average, there is no pair coming from X' to X. However, the pattern of detections in S and I is not that in one of two trials are detected three s-i pairs and in the other trial is detected only one s-i pair. No, in general, there are two detections per trial. Therefore a 2-wave from X' is present in each trial. Then, what we can assume is that in one trial comes a full 2-wave from X', and in another trial comes an empty 2-wave from X'.

In this way the condition (14) is fulfilled in every trial.

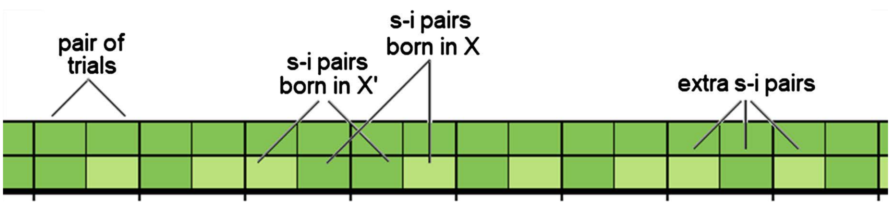

Figure 4. Full and empty waves.

Several trials of the experiment **II** are shown. The trials are grouped in pairs. In one of the two trials in a pair, is detected a full s-i pair coming from the crystal X'. Three more pairs are detected which were born in X. Two of these are extra-pairs (upper rectangles) born in X due to the fact that the condition (14) is fulfilled. The occurrence of a full s-i pair is depicted by painting the rectangle in green. The extra-pairs are always full 2-waves. In one of two trials, only empty 2-waves come from X'. The respective rectangles are painted in light-green.

In the case **B**, the 2-waves, one from E' and one generated in X within the fascicle coming from E', annihilate one another in the crystal X according with the phase condition (16). However, as shown above, the full s-i pair from X' comes only in one of two trials. Thus, the condition (16) can be fulfilled in each trial if in the other trial an empty 2-wave comes from X'.

5. Conclusions

An experiment was described and analyzed according to the quantum formalism, and after that, under the assumption of full and empty waves. Two cases were given special attention, one in which the yield of s-i pairs is enhanced, and one in which the yield is inhibited. It was shown that for these cases, it is necessary to admit the existence of empty waves.

There is no claim here that the hypothesis of full and empty waves is the only way of interpreting the process occurring during the measurement of a quantum system, neither is claimed here that the measurement problem is fully solved by admitting this hypothesis. The purpose of the present work is to show an experiment in which this hypothesis offers a very plausible explanation of the measurement process.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Abbreviations

2-wave = two-particle wave
dBB = de Broglie-Bohm
DC = down-conversion
QM = quantum mechanics
s-i = signal-idler
UV = ultraviolet
w-f = wave-function
w-p = wave-packet