Scientific Research Publishing

The Wave Function Cannot Be a Real Wave—Then, Can We Speak of an Ontology of Particles?

Sofia D. Wechsler

Independent Researcher, Kiryat Motzkin, Israel
Email: sofia10@012.net.il

Abstract

Is the wave-function a physical reality traveling through our apparatus? Is it a real wave, or it is only a mathematical tool for calculating probabilities of results of measurements? Different interpretations of the quantum mechanics (QM) assume different answers to this question. It is shown in this article that the assumption that the wave-function is a real wave entails a contradiction with the predictions of the QM, when the special relativity is invoked. Therefore, this text concentrates on interpretations that conjecture that the reality that moves in our apparatuses is particles, and they move under the constraints of the wave-function. The de Broglie-Bohm interpretation, which matches this picture, assumes that the particle travels along a continuous trajectory. However, the idea of continuous trajectories was proved to lead to a contradiction with the quantum predictions. Therefore this interpretation is not considered here. S. Gao conjectured that the particle is in a permanent random and discontinuous motion (RDM). As it jumps all the time from place to place, the total set of occupied positions at a certain time is given by the absolute square of the wave-function. As motivation for his idea, Gao argued that if a charged particle were simultaneously in two or more locations at the same time, the copies of the particle would repel one another, destroying the wave-function. It is proved here that the quantum formalism renders this motivation wrong. Although refuting this motivation, the RDM interpretation is examined here. A couple of problems of this interpretation are examined and it is proved that they don't lead to any observable contradictions with the QM predictions, except one problem which seems to have no solution. In all, it appears that none of the wide-spread interpretations of the QM is free of contradictions.

Keywords

Quantum Mechanics, Quantum Particle, Ontology, Self-Interaction,

Instantaneous Condition, Special Relativity

1. Introduction

The question whether the wave-function (w-f) is or is not a real wave traveling in our apparatus, has preoccupied for a long time the physicists. Pusey, Barrett and Rudolph (PBR) [1] [2], proved that the w-f must have a realistic counterpart that travels in our apparatus and that differs from one w-f to another. The most widespread interpretations of QM agree with this conclusion which seems almost trivial; indeed, in our apparatus must travel some real entity, and must differ from one w-f to a different one for producing different effects when tested.

- The de Broglie-Bohm (dBB) mechanics [3] [4] [5], assumes that the quantum object (QO) that travels in our apparatus consists of two items, a *particle* and a *wave*. The latter guides the trajectory of the particle by determining which trajectories are allowed and which are forbidden. However, the dBB mechanics conjectures that a particle cannot appear out of nothing and disappear into nothing. Therefore its trajectory must be continuous and not split. It was proved that the assumption of continuity of trajectories leads to a contradiction, [6]. Therefore this interpretation is not examined here.

- The "consistent histories" interpretation [7] [8] [9] [10] speaks in terms of *waves*. However, while claiming that it explains the measurement process without using the collapse postulate, in fact, in each history of a quantum system appears the collapse from a superposition of states to one of the members of the superposition, see examples in the Chapter 12 and 13 of [8].

- The "transactional" interpretation [11] [12] [13] [14], suggests the existence of two types of *waves*. One is identical to the w-f, it is emitted by the source of the QO toward the detectors, and travels forward in time; the other type of waves, alien to the quantum formalism, is emitted by the detectors and travels backward in time. A "hand-shake" is postulated to occur between the wave from the source and the wave from one of the detectors, and that determines which detector would click.

- Ghirardi, Rimini, Weber, Pearle, Gisin, and others, accepted the collapse of the w-f as a real phenomenon caused by a perturbing field [15]-[27]. The most advanced form of this proposal—the CSL model of collapse—is examined in detail in [27]. No clear claim is made that the w-f is considered a real wave, but this interpretation does not speak of a particle. The perturbing field is supposed, in some works, to be the gravitational field [28]-[33]. However, this interpretation is problematic when applied to entanglements. For instance, if an experiment is performed dynamically, if the experimentalists change their minds and change the configuration of their apparatuses during the measurement (e.g. in an experiment with the photon singlet they change during the experiment the orientations of the polarizers) the per-

turbing field should change according to their choices. No physical field changes according to human choices. D. Bedingham [34] tried to tailor a perturbing field to the polarization singlet, but he did not offer a solution to the mentioned problem.

- S. Gao [35] [36] [37] [38], assumes that the w-f is a statistical entity, in the sense that the region occupied by the allowed positions of a particle at a given time determines the absolute square of the w-f at that time. The particle is supposed to be in a random discontinuous motion (RDM), *i.e.* jump from place to place. Thus, what has reality in Gao's interpretation of the QM is the particle, and the w-f is just a mathematical tool.

Only the Copenhagen interpretation of QM makes an exception [39]: it does not speak of a really existing item as PBR proved, be it wave or particle, it just doesn't deal with question of the w-f realism, but only with its predictions for tests results. The w-f is considered something that comprises all the information about the QO.

It is proved in the present article that the option that the w-f is a real wave, leads to a contradiction. Therefore, the idea that what travels in our apparatus is a particle, is examined. And since continuous trajectories are impossible, these particles should jump from a region of the space to another one, as conjectures the RDM interpretation. Gao motivated his interpretation of the QM as follows:

"If the wave function represents a physical field, then it seems odd that there are (electromagnetic and gravitational) interactions between the fields of two electrons but no interactions between two parts of the field of an electron" [37].

The present text proves that this motivation is wrong, as the behavior of the QO is dictated by quantum laws, not by classical ones. But that does not invalidate the RDM interpretation. On the other hand it is shown here that this interpretation is not free of problems either, especially vis-à-vis the special relativity. In his work [35] Gao himself points to difficulties of the RDM. This text offers solutions for some of the difficulties, but has no solution for the problem with the special relativity.

Note: in this article the expression "quantum particle" is frequently used. It may mean an elementary particle, or an atom or molecule for which the internal structure is ignored. In any case, the respective item is considered as described by the QM, not by the classical physics.

The rest of the sections are organized as follows: Section 2 shows that the assumption of onticity of the w-f leads to a problem with the special relativity. Section 3 proves that the quantum formalism forbids interaction between two parts of the w-f of the same QO. Sections 4 and 5 try to apply the RDM to entanglements and shows that difficulties are encountered. For some of them, solutions are proposed, but there is a problem vis-à-vis the special relativity for which no solution can be suggested. Section 6 contains conclusions.

2. The Assumption of Onticity of the Wave-Function Has Problems with the Special Relativity

Consider an entanglement of two particles 1 and 2 entangled by the paths on which they travel

$$|\psi\rangle = \left(|a\rangle|b\rangle + |c\rangle|d\rangle\right)\big/\sqrt{2}. \tag{1}$$

On the four paths *a*, *b*, *c* and *d*, are placed non-absorbing detectors.

Consider a trial of the experiment in which at the time t_1 by the clock of the lab—the frame S—the particle 1 is tested and found on the path a. Therefore, for any $t > t_1$ the particle 2 should travel on the path *b*. Indeed, at a time $t_2 > t_1$ at which the particle 2 is detected it is found on the path *b*. The w-f of the pair of particles between the two events of detection should be reduced to $|a\rangle|b\rangle$.

Let now S' be a frame of coordinates in movement with respect to the lab and a clock C' which moves together with the frame S'. The movement of this frame is such that the detection of the particle 2 occurs first, at a time t'_2 according to C'. The detection of the particle 1 occurs at t'_1, with $t'_1 > t'_2$.

Let's notice that according to S' no detection is performed before t'_2, therefore the w-f of the pair of particles before the detection of the particle 2 must be (1). But returning to the frame S, after the detection of particle 1 and before the detection of particle 2, the w-f is $|a\rangle|b\rangle$.

The conclusion is that the w-f is ambiguously defined; therefore it cannot be ontic, *i.e.* a real wave traveling through our apparatus.

3. The Wave-Function Is Not Self-Interacting

Eliminating the possibility that the w-f is a physical reality, it remains that the entity traveling in our apparatus is a particle. It was proved in [38] that if the w-f of an electrically charged particle consists in several wave-packets (w-ps), the charge has to be present in each one of the w-ps. Then, the w-ps should repel one another. But no experiment proved such an effect of repulsion. For explaining the absence of such an effect, S. Gao proposed the idea that the particle jumps from w-p to w-p, [37].

However, there is no need to invent jumps for explaining the lack of self-interaction of the w-f. The quantum world behaves differently than the classical rules dictate. Let the w-f of an electron consist in two w-ps $|\psi\rangle_A$ and $|\psi\rangle_B$. According to the second quantization one can write it as

$$|\psi\rangle = \left(\psi_A |1\rangle_A |0\rangle_B + \psi_B |0\rangle_A |1\rangle_B\right)\big/\sqrt{2}, \tag{2}$$

The quantum formalism distinguishes, as well as the classical physics, between two modes of association of events:

- Logical AND between two events A and B. That means that they occur together. In the w-f (2), the w-p $|1\rangle_A$ does not have an effect together with the w-p $|1\rangle_B$, but together with the w-p $|0\rangle_B$. If the w-p ψ_A is populated with the charge, the electric force of the charge cannot repel the w-p ψ_B because ψ_B is empty, $|0\rangle_B$, Analogously if ψ_B is occupied. Therefore, ψ_A and

ψ_B cannot interact.

- Logical OR means that the events A and B are alternative: either A have an effect, or B. In the w-f (2) the presence of the electron in the w-ps $|1\rangle_A$ and $|1\rangle_B$, are alternative situations. Either $|1\rangle_A$ has an effect, or $|1\rangle_B$, but they do not have effects together.

These rules are the same as in the classical physics with one great difference: in the classical physics $\psi_A|1\rangle_A$ and $\psi_B|1\rangle_B$ do not produce interference.

4. The RDM Interpretation of QM vs. Delayed Tests and vs. the Special Relativity

In his work [35] Gao discusses a couple of difficulties of the RDM interpretation.

These difficulties and additional ones are discussed in this section. For some of the difficulties a solution is proposed.

In the Section 7.2.3 of [35] Gao considered two particles, 1 and 2, entangled by position such that when the particle 1 occupies the position $\mathbf{r}_1 = (x_1, y_1, z_1)$, the particle 2 occupies the position $\mathbf{r}_2 = (x_2, y_2, z_2)$, and when the particle 1 occupies the position $\mathbf{r}_3 = (x_3, y_3, z_3)$, the particle 2 occupies the position $\mathbf{r}_4 = (x_4, y_4, z_4)$. Gao assumes that at some time the particle 1 is at $\mathbf{r}_1$ and particle 2 at $\mathbf{r}_2$, and when particle 1 jumps from $\mathbf{r}_1$ to $\mathbf{r}_3$, exactly at the same time the particle 2 jumps from $\mathbf{r}_2$ to $\mathbf{r}_4$.

However, the experimental practice shows that an entanglement remains true also when the two particles are tested at different times. Let particle 1 be tested at t_1, exactly after it jumped from $\mathbf{r}_1$ to $\mathbf{r}_3$. Therefore it would be found at $\mathbf{r}_3$. According to Gao's conjecture, the particle 2 jumps at this time from $\mathbf{r}_2$ to $\mathbf{r}_4$. At a later time t_2 the particle 2 is tested, when it jumps back to $\mathbf{r}_2$. If the particle 1 were not detected already and found at $\mathbf{r}_3$, it would have jumped back to $\mathbf{r}_1$. But that does not happen anymore.

Bottom line, according to Gao's conjecture, if the particles are detected at different times, the entanglement is violated.

For solving this problem a mechanism should be proposed by which the detection of one particle induces freezing of the other particle in the situation required by the entanglement. Though, from the point of a moving observer for which the particle 2 is tested first, the freezing mechanism must act backwards in time.

Another problem, described by Gao in the Section 9.1.1 of [35], is the duplication of the particle. Consider a w-f consisting of two w-ps ψ_A and ψ_B distant from one another. Let the particle be at a time t_1 at the point x_1 of ψ_A according to a frame of coordinates S, and consider that it jumps at a time $t_2 > t_1$ to the point x_2 of ψ_B. According to another frame of coordinates, S', moving with respect to S with the velocity v, the times and space coordinates are modified as follows

$$t_1' = \left(t_1 - x_1 v/c^2\right)\Big/\sqrt{1 - v^2/c^2} \ , \quad t_2' = \left(t_2 - x_2 v/c^2\right)\Big/\sqrt{1 - v^2/c^2} \ , \tag{3}$$

$$x_1' = (x_1 - t_1 v)\Big/\sqrt{1 - v^2/c^2}\,, \quad x_2' = (x_2 - t_2 v)\Big/\sqrt{1 - v^2/c^2}\,, \qquad (4)$$

Setting $t_2' = t_1'$ one gets

$$v = \frac{(t_2 - t_1)c^2}{x_2 - x_1}\,. \qquad (5)$$

If the jump is nonlocal, *i.e.* the distance between the two w-ps and therefore between x_1 and x_2, is greater than $(t_2 - t_1)c$, there results $v < c$. Therefore there exists a frame S' by which the particle is simultaneously in the two w-ps.

This situation cannot be detected experimentally. If an absorbing detector is placed on the way of the w-p ψ_A containing the position x_1, it absorbs the particle at t_1, so the particle cannot jump anymore to the w-p ψ_B.

If the detector is not absorbing, that means that the particle is entangled with another particle, let's name it "ancilla", which has two states, a state $|\xi_1\rangle$ for the main particle being at x_1, and a state $|\xi_2\rangle$ for the main particle being at x_2. If the detector absorbs the ancilla in the state $|\xi_1\rangle$ at the time t_1, the ancilla cannot be re-detected by another detector at the time t_2 in a state $|\xi_2\rangle$.

The complementary problem is described by Gao in Section 9.1.3 of his work [35]. Consider the w-f $|\psi\rangle = (|\psi_A\rangle + |\psi_B\rangle)\big/\sqrt{2}$. Let S be the lab frame of coordinates, according to which the two w-ps are tested simultaneously at the time t_1. Consider a trial of the experiment in which the w-f collapses on $|\psi_A\rangle$, therefore $|\psi_B\rangle$ vanishes at the same time. Let S' be a frame according to which $|\psi_A\rangle$ meets a detector at the time t'_1 and $|\psi_B\rangle$ meets a detector at the time t'_2, with $t'_1 > t'_2$. That means, in the interval of time $t'_1 - t'_2$ the detector on $|\psi_B\rangle$ remained silent, and the detector on $|\psi_A\rangle$ wasn't met yet. What remained from the w-f $|\psi\rangle$ is the part $|\psi_A\rangle\big/\sqrt{2}$, which means that the particle is in $|\psi_A\rangle$ with the probability 1/2, while with another probability 1/2 it jumps backward in time, *i.e.* before t'_2, to $|\psi_B\rangle$. In short, the particle is present in $|\psi_A\rangle$ only part of the interval $t'_1 - t'_2$, and during the other part the particle is absent from the space.

This problem too is not observable, what is observable is only what the detectors report. Besides that, the work of the team of S. Savasta, [40], showed that the energy/number-of-particles should be conserved in the states that are detectable, but not in intermediate states (see also [41]).

In the Section 9.1.2 if [35] Gao turns to entanglements and describes a more complex problem. Let the entanglement of the particles A and B be prepared as $(|\psi_u\rangle|\varphi_u\rangle + |\psi_d\rangle|\varphi_d\rangle)\big/\sqrt{2}$ where $|\psi_u\rangle$, $|\psi_d\rangle$ are states of the particle A, and $|\varphi_u\rangle$, $|\varphi_d\rangle$ are states of the particle B. The four w-ps are supposed to travel in regions distanced from one another two by two. Let $t_{1,A}$ be the time at which the particle A jumps from $|\psi_u\rangle$ and let $t_{2,A}$ be the time at which the jump is completed and particle A lands in the w-p $|\psi_d\rangle$, Let $t_{1,B}$ be the time at which the particle B leaves the w-p $|\varphi_u\rangle$ and let $t_{2,B}$ be the time at which it lands in the w-p $|\varphi_d\rangle$. The times $t_{1,A}$, $t_{1,B}$, $t_{2,A}$ and $t_{2,B}$ are readings of the clock in the lab frame of coordinates, S, with $t_{2,A} > t_{1,A}$, $t_{2,B} > t_{1,B}$. Let also $t_{2,B} > t_{1,A}$.

Then one can find a frame of coordinates S' in movement with respect to S with the velocity

$$v = \frac{\left(t_{2,B} - t_{1,A}\right)c^2}{x_{2,B} - x_{1,A}}.$$

(6)

In this frame $t'_{2,B} = t'_{1,A}$, with

$$t'_{2,B} = \frac{x_{2,B}t_{1,A} - t_{2,B}x_{1,A}}{\left(x_{2,B} - x_{1,A}\right)\sqrt{1 - v^2/c^2}}.$$

(7)

The equality $t'_{2,B} = t'_{1,A}$ means that by the time the particle B lands in the w-p $|\varphi_d\rangle$, the particle A is in $|\psi_u\rangle$ and is leaving this w-p.

This is a violation of the entanglement.

However, neither this effect could be observed experimentally if Gao would conjecture the existence of a frame S by which once one particle is detected, the other particle stops jumping. If particle A is tested first by this frame and found in $|\psi_u\rangle$ ($|\psi_d\rangle$) the particle B is frozen inside $|\varphi_u\rangle$ ($|\varphi_d\rangle$) until is detected. Then, there are no $t_{2,B}$ and $x_{2,B}$ and the Equation (6) has no meaning. By any other frame, no matter what is the order of detection of the particles, the results of the detections will be the same as in S.

A more severe problem, that yes is experimentally observed, is separately presented in the next section.

5. A Variant of Hardy's Paradox

Let's consider a pair of particles, p[+] and p[−], entangled by the path of flight— **Figure 1**. The w-f is

$$|\psi\rangle = \left(\imath|\mathbf{u}^+\rangle|\mathbf{v}^-\rangle + |\mathbf{v}^+\rangle|\mathbf{v}^-\rangle + \imath|\mathbf{v}^+\rangle|\mathbf{u}^-\rangle\right)\big/\sqrt{3}\ ^1.$$

(8)

This experiment was proposed and analyzed for the first time by L. Hardy [43], and is known in the literature under the name "Hardy's paradox"—see also [44]. Here it is presented in a modified form which allows testing the QM predictions by direct measurements.

At the beam-splitters **BS**[±] occur the transformations

$$|\mathbf{u}^\pm\rangle \rightarrow \left(|\mathbf{c}^\pm\rangle + \imath|\mathbf{d}^\pm\rangle\right)\big/\sqrt{2}, \quad |\mathbf{v}^\pm\rangle \rightarrow \left(\imath|\mathbf{c}^\pm\rangle + |\mathbf{d}^\pm\rangle\right)\big/\sqrt{2}.$$

(9)

Introducing them in (8) one gets

$$|\phi\rangle = \left(-3|\mathbf{c}^+\rangle|\mathbf{c}^-\rangle + \imath|\mathbf{c}^+\rangle|\mathbf{d}^-\rangle + \imath|\mathbf{d}^+\rangle|\mathbf{c}^-\rangle - |\mathbf{d}^+\rangle|\mathbf{d}^-\rangle\right)\big/\sqrt{12}.$$

(10)

The relevant term in this w-f is $|\mathbf{d}^+\rangle|\mathbf{d}^-\rangle$ implying that if the detectors were moved to the paths $\mathbf{c}^+$, $\mathbf{d}^+$, $\mathbf{c}^-$, $\mathbf{d}^-$, the detectors D[+] and D[−] would click simultaneously. The probability of obtaining this joint detection would be 1/12. Returning to the **Figure 1** with the detectors on the paths $\mathbf{u}^\pm$ and $\mathbf{v}^\pm$, by the RDM interpretation, prior to meeting the beam-splitters BS'[±] the two particles were on the paths $\mathbf{d}^+$ and $\mathbf{d}^-$ respectively, with the probability 1/12.

The transformations at the beam-splitters BS'[±] and taking also in consideration the phase-shifts, are

---

[1]This w-f was prepared experimentally by Lundeen *et al.* [42].
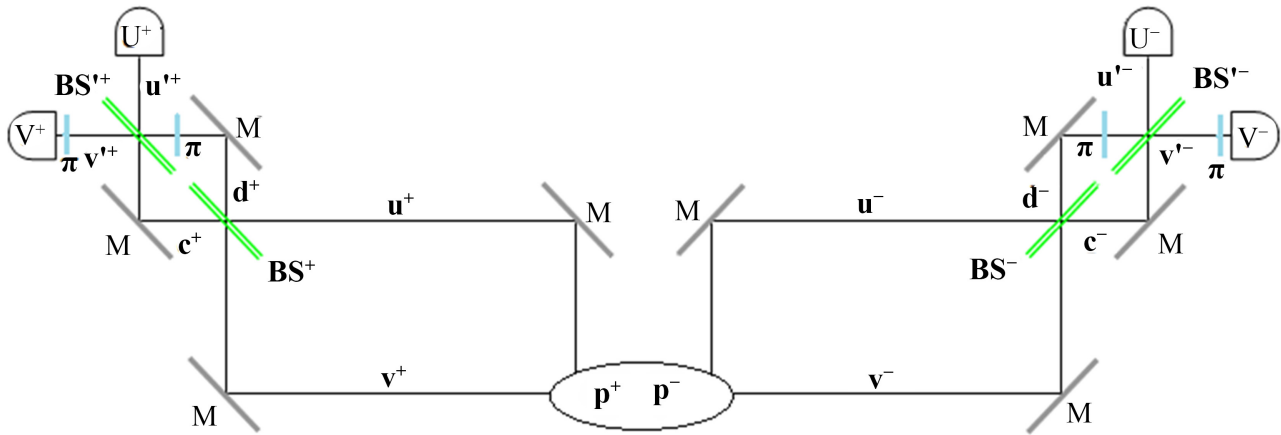
Figure 1. An experiment with a two-particle entanglement. $\mathbf{u}^{\pm}$, $\mathbf{v}^{\pm}$, $\mathbf{c}^{\pm}$, $\mathbf{d}^{\pm}$, $\mathbf{u}'^{\pm}$, $\mathbf{v}'^{\pm}$, are directions of flight of the particles. $\mathbf{BS}^{\pm}$ and $\mathbf{BS}'^{\pm}$ are beam-splitters. M are mirrors. $\mathbf{U}^{\pm}$ and $\mathbf{V}^{\pm}$ are detectors. The region $\mathbf{p}^{+}\mathbf{p}^{-}$ is the preparation region of the entanglement. π symbolize phase-shifters by π.

$$\left|\mathbf{c}^{\pm}\right\rangle \to \left(\left|\mathbf{u}'^{\pm}\right\rangle - \iota\left|\mathbf{v}'^{\pm}\right\rangle\right)\big/\sqrt{2}\, , \quad \left|\mathbf{d}^{\pm}\right\rangle \to -\left(\iota\left|\mathbf{u}'^{\pm}\right\rangle - \left|\mathbf{v}'^{\pm}\right\rangle\right)\big/\sqrt{2}\, . \tag{11}$$

Introducing them in (10) one gets back the initial w-f (8):

$$\left|\psi'\right\rangle = \left(\iota\left|\mathbf{u}'^{+}\right\rangle\left|\mathbf{v}'^{-}\right\rangle + \iota\left|\mathbf{v}'^{+}\right\rangle\left|\mathbf{u}'^{-}\right\rangle + \left|\mathbf{v}'^{+}\right\rangle\left|\mathbf{v}'^{-}\right\rangle\right)\big/\sqrt{3}\, . \tag{12}$$

Let's now imagine that the setup in the **Figure 1** is sufficiently wide so that one can find a frame of coordinates S' flying in the direction from BS'$^-$ to BS'$^+$, on whose time axis, by the time the detector U$^+$ clicks, the w-ps of p$^-$ didn't reach yet BS'$^-$. Introducing in (10) the transformations (11) only for the particle p$^+$, one gets

$$\left|\phi^{+}\right\rangle = \left(2\iota\left|\mathbf{v}'^{+}\right\rangle\left|\mathbf{c}^{-}\right\rangle + \left|\mathbf{u}'^{+}\right\rangle\left|\mathbf{c}^{-}\right\rangle + \iota\left|\mathbf{u}'^{+}\right\rangle\left|\mathbf{d}^{-}\right\rangle\right)\big/\sqrt{6}\, . \tag{13}$$

One can see that by the time, on the time axis of S', that while the particle p$^-$ travels along the path d$^-$, p$^+$ must click the detector U$^+$.

But one can also find a frame of coordinates S" flying in the direction from BS'$^+$ to BS'$^-$, on whose time axis, by the time the detector U$^-$ clicks, the w-ps of p$^+$ didn't reach yet BS'$^+$. Introducing in (10) the transformations (11) only for the particle p$^-$, one gets

$$\left|\phi^{-}\right\rangle = \left(2\iota\left|\mathbf{c}^{+}\right\rangle\left|\mathbf{v}'^{-}\right\rangle + \left|\mathbf{c}^{+}\right\rangle\left|\mathbf{u}'^{-}\right\rangle + \iota\left|\mathbf{d}^{+}\right\rangle\left|\mathbf{u}'^{-}\right\rangle\right)\big/\sqrt{6}\, . \tag{14}$$

That implies that by the time, according to S", that while the particle p$^+$ travels along the path d$^+$, p$^-$ must click the detector U$^-$.

Returning now to the frame of coordinates of the lab with respect to which the source, the beam-splitters and the mirrors are at rest, the w-f of the two particles is (12). And it can't allow both detectors U$^+$ and U$^-$ click together because it contains no combination $\left|\mathbf{u}'^{+}\right\rangle\left|\mathbf{u}'^{-}\right\rangle$.

According to the RDM interpretation the two particles should travel simultaneously on the paths d$^+$ and d$^-$, but if the requirements of the special relativity are taken in consideration, one comes to a contradiction.

6. Conclusion

The most widespread interpretations of the QM were examined here and it was shown that they present inconsistencies. Along with this, it was shown that the idea that the w-f is a real wave, has problems with the special relativity. One would then turn to the option that the w-f is just a tool for calculating probabilities of results of measurements, and what is real in the QOs are particles. Since it was proved that the particles can't follow continuous trajectories, they should jump at random from place to place. Thus, one is led to Gao's RDM interpretation of the QM. It was though proved here that neither this interpretation can overcome the difficulties with the special relativity. Thus, it appears that none of the most wide-spread interpretations of the QM is free of problems.

Conflicts of Interest

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

References

[1] Pusey, M.F., Barrett, J. and Rudolph, T. (2012) On the Reality of the Quantum State, *Nature Physics*, **8**, 475-478. https://doi.org/10.1038/nphys2309

[2] Leifer, M.S. (2014) Is the Quantum State Real? An Extended Review of ψ-Ontology Theorems. *Quanta*, **3**, 67-155. https://doi.org/10.12743/quanta.v3i1.22

[3] De Broglie, L. (1926) Ondes et Mouvements. Villars, G., Paris.

[4] De Broglie, L. (1924) Recherches sur la théorie des quanta. Ph.D. Thesis, Migration Université en cours d'affectation, Français. https://doi.org/10.1051/anphys/192510030022

[5] Bohm, D. (1952) A Suggested Interpretation of the Quantum Theory in Terms of "Hidden" Variables I. *Physical Review*, **85**, 166-179. https://doi.org/10.1103/PhysRev.85.166

[6] Wechsler, S.D. (2022) A Non-Relativistic Argument against Continuous Trajectories of Particles. *Journal of Quantum Information Science*, **12**, 29-36. https://doi.org/10.4236/jqis.2022.122004

[7] Griffiths, R.B. (1984) Consistent Histories and the Interpretation of Quantum Mechanics. *Journal of Statistical Physics*, **36**, 219-272. https://doi.org/10.1007/BF01015734

[8] Griffiths, R.B. (2002) Consistent Quantum Theory. Cambridge University Press, Cambridge.

[9] Griffiths, R.B. (2014) The Consistent Histories Approach to Quantum Mechanics. *Stanford Encyclopedia of Philosophy*, Stanford.

[10] Griffiths, R.B. (2002) Consistent Resolution of Some Relativistic Quantum Paradoxes. *Physical Review A*, **66**, Article ID: 062101. https://doi.org/10.1103/PhysRevA.66.062101

[11] Cramer, J.G. (1986) The Transactional Interpretation of the Quantum Mechanics. *Reviews of Modern Physics*, **58**, 647-688. https://doi.org/10.1103/RevModPhys.58.647

[12] Cramer, J.G. (1988) An Overview of the Transactional Interpretation. *International*

Journal of Theoretical Physics, **27**, 227-236. https://doi.org/10.1007/BF00670751

[13] Cramer, J.G. (2015) The Quantum Handshake: Entanglement, Nonlocality and Transactions. Springer, Cham.

[14] Kastner, R.E. and Cramer, J.G. (2017) Quantifying Absorption in the Transactional Interpretation. Cornell University, Ithaca. https://doi.org/10.1103/PhysRevD.34.470

[15] Ghirardi, G.-C., Rimini, A. and Weber, T. (1986) Unified Dynamics for Microscopic and Macroscopic Systems. *Physical Review D*, **34**, Article 470.

[16] Pearle, P. (1989) Combining Stochastic Dynamical State-Vector Reduction with Spontaneous Localization. *Physical Review A*, **39**, Article ID: 2277. https://doi.org/10.1103/PhysRevA.39.2277

[17] Ghirardi, G.-C., Pearle, P. and Rimini, A. (1990) Markov Processes in Hilbert Space and Continuous Spontaneous Localization of Systems of Identical Particles. *Physical Review A*, **42**, Article 78. https://doi.org/10.1103/PhysRevA.42.78

[18] Pearle, P. (2007) Collapse Models. ArXiv: quant-ph/9901077v1.

[19] Bassi, A. and Ghirardi, G.-C. (2003) Dynamical Reduction Models. *Physics Reports*, **379**, 257-426. https://doi.org/10.1016/S0370-1573(03)00103-0

[20] Adler, S. (2007) Lower and Upper Bounds on CSL Parameters from Latent Image Formation and IGM Heating. *Journal of Physics A*, **40**, 2935. https://doi.org/10.1088/1751-8113/40/12/S03

[21] Adler, S. and Bassi, A. (2007) Collapse Models with Non-White Noises. *Journal of Physics A*, **40**, Article ID: 15083. https://doi.org/10.1088/1751-8113/40/50/012

[22] Bassi, A. and Salvetti, D.G.M. (2007) The Quantum Theory of Measurement within Dynamical Reduction Models. ArXiv: quant-ph/070201011v1.

[23] Bassi, A., Lochan, K., Satin, S., Singh, T.P. and Ulbricht, H. (2013) Models of Wave-function Collapse, Underlying Theories, and Experimental Tests. ArXiv: quant-ph/1204.4325v3.

[24] Carlesso, M. and Donadi, S. (2019) Collapse Models: Main Properties and the State of Art of the Experimental Tests. In: Vacchini, B., Breuer, H.P. and Bassi, A., Eds., *Advances in Open Systems and Fundamental Tests of Quantum Mechanics*, Vol. 237, Springer, Cham, 1-13. https://doi.org/10.1007/978-3-030-31146-9_1

[25] Gisin, N. (1984) Quantum Measurements and Stochastic Processes. *Physical Review Letters*, **52**, Article 1657. https://doi.org/10.1103/PhysRevLett.52.1657

[26] Gisin, N. (2018) Collapse. What Else? In: Gao, S., Ed., *Collapse of the Wave Function*, Cambridge University Press, Cambridge, 207.

[27] Wechsler, S.D. (2020) In Praise and in Criticism of the Model of Continuous Spontaneous Localization of the Wave-Function. *Journal of Quantum Information Science*, **10**, 73-103. https://doi.org/10.4236/jqis.2020.104006

[28] Diósi, L. (1987) A Universal Master Equation for the Gravitational Violation of Quantum Mechanics. *Physics Letters A*, **120**, 377-381. https://doi.org/10.1016/0375-9601(87)90681-5

[29] Diósi, L. (1989) Models for Universal Reduction of Macroscopic Quantum Fluctuations. *Physics Reviews A*, **40**, Article 1165. https://doi.org/10.1103/PhysRevA.40.1165

[30] Diósi, L. (2007) Notes on Certain Newton Gravity Mechanisms of Wave Function Localisation and Decoherence. *Journal of Physics A*: *Mathematical and Theoretical*, **40**, Article 2989. https://doi.org/10.1088/1751-8113/40/12/S07

[31] Bahrami, M., Smirne, A. and Bassi, A. (2014) Gravity and the Collapse of the Wave

Function: A Probe into Diósi-Penrose Model. *Physical Review A*, **90**, Article ID: 062105. https://doi.org/10.1103/PhysRevA.90.062105

[32] Gasbarri, G., Toroš, M., Donadi, S. and Bassi, A. (2017) Gravity Induced Wave Function Collapse. *Physical Review D*, **96**, Article ID: 104013. https://doi.org/10.1103/PhysRevD.96.104013

[33] Donadi, S., Piscicchia, K., Curceanu, C., Diósi, L., Laubenstein, M. and Bassi, A. (2021) Underground Test of Gravity-Related Wave Function Collapse. *Nature Physics*, **17**, 74-78. https://doi.org/10.1038/s41567-020-1008-4

[34] Bedingham, D.J. (2009) Dynamical State Reduction in an EPR Experiment. *Journal of Physics A*: *Mathematical and Theoretical*, **42**, Article ID: 465301. https://doi.org/10.1088/1751-8113/42/46/465301

[35] Gao, S. (2016) The Meaning of the Wave Function: In Search of the Ontology of Quantum Mechanics. ArXiv: quant-ph/1611.02738v1.

[36] Gao, S. (2018) Is an Electron a Charge Cloud? A Reexamination of Schrödinger's Charge Density Hypothesis. *Foundations of Science*, **23**, 145-157. https://doi.org/10.1007/s10699-017-9521-3

[37] Gao, S. (2020) A Puzzle for the Field Ontologists. *Foundations of Physics*, **50**, 1541-1553. https://doi.org/10.1007/s10701-020-00390-0

[38] Wechsler, S. (2021) About the Nature of the Quantum System—An Examination of the Random Discontinuous Motion Interpretation of the Quantum Mechanics. *Journal of Quantum Information Science*, **11**, 99-111. https://doi.org/10.4236/jqis.2021.113008

[39] Faye, J. (2002) Copenhagen Interpretation of Quantum Mechanics. *Stanford Encyclopedia of Philosophy*, Stanford. http://plato.stanford.edu/entries/qm-copenhagen/

[40] Garziano, L., Macrì, V., Stassi, R., Di Stefano, O., Nori, F. and Savasta, S. (2016) A Single Photon Can Simultaneously Excite Two or More Atoms. ArXiv: quant-ph/1601.00886v2.

[41] Wechsler, S. (2019) The Wave-Particle Duality—Does the Concept of Particle Make Sense in Quantum Mechanics? Should We Ask the Second Quantization? *Journal of Quantum Information Science*, **9**, 155-170. https://doi.org/10.4236/jqis.2019.93008

[42] Lundeen, J.S. and Steinberg, A.M. (2009) Experimental Joint Weak Measurement on a Photon Pair as a Probe of Hardy's Paradox. ArXiv: quant-ph/0810.4229.

[43] Hardy, L. (1992) Quantum Mechanics, Local Realistic Theories, and Lorenz-Invariant Realistic Theories. *Physical Review Letters*, **68**, Article 2981. https://doi.org/10.1103/PhysRevLett.68.2981

[44] Wechsler, S.D. (2017) Hardy's Paradox Made Simple—What We Infer from It? https://www.researchgate.net/publication/318446904_Hardy's_paradox_made_simple_-_what_we_infer_from_it

Abbreviations

dBB = De Broglie-Bohm;

CSL = Continuous spontaneous localization;

QM = Quantum mechanics;

QO = Quantum object;

PBR = Pusey, Barrett and Rudolph;

RDM = Random, discontinuous motion;

w-f = Wave-function;

w-p = Wave-packet.