A Causal and Local Interpretation of Experimental Realization of Wheeler's Delayed-choice Gedanken Experiment

J. E. F. Araújo†, J. L. Cordovil†, J. R. Croca†, R. N. Moreira† and A. R. da Silva‡.
†Centro de Filosofia das Ciências da Universidade de Lisboa Faculdade de Ciências da Universidade de Lisboa Campo Grande, Ed. C1, 3º Piso, Sala 4.3.24 1749-016 Lisboa, Portugal, ‡Instituto Superior Técnico, Universidade Técnica de Lisboa

Abstract: Recently the experimental group of A. Aspect published a very interesting experimental realization of the well known Wheeler's delayed-choice Gedanken Experiment. In the paper the authors refer to the usual, non causal linear explanation of the experiment. In the present work we show how it is possible, and furthermore desirable, to explain the same experiment in terms of the modern local causal and nonlinear quantum theory, inspired in the work of the great physicist Louis de Broglie. In this way we are able to get rid of the mysteries and of the weird features of the orthodox interpretation, like retractions in time, and therefore recover causality and rationality once more.

Keywords: Fundamental quantum physics, nonlinear causal and local quantum physics, orthodox quantum theory, Wheeler's delayed-choice Gedanken Experiment, local wavelet analysis, Fourier ontology.

1. Introduction

Wheeler's delayed-choice Gedanken Experiment [1] is a kind of thought experiment. The initial experiment runs like this:

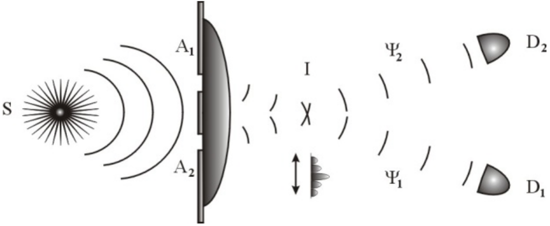

Fig. 1 – Setup of Wheeler's delayed-choice experiment.

As shown in Fig.1, a monophotonic source S, delivers one photon at a time. This photon impinges on a screen with two apertures, A1 and A2. Behind it is placed a plane convergent lens. The two emerging beams converge and overlap at the interference zone I. After the mixing region, the beams diverge following different independent paths going to detectors D1 and D2.

If the corpuscle is "seen" at detector D1, we would say, following the orthodox interpretation, that the photon has followed path A1D1. If detected at D2 it has followed the other possible path A2D2. This means that the photon emitted by source S follows either the path A1D1 or A2D2.

Now if we place a detector, a photographic plate, in the zone where the two beams overlap, after a certain time a nice interference pattern is seen there. This means that the photon follows both paths at the same time. Summarizing: according to Wheeler, when the detector is removed, the photon follows either one path or the other. When the detector is placed in position, the photon follows both paths at the same time. Notice that the "decision" to follow along one single path or both paths at the same time depends on the placement of the detector at the mixing region. Furthermore this action is done long after the photon has had the possibility of crossing the holes A1 or/and A2. Because of the fact that the "decision", the "choice", of following one or both paths is made post-factum, Wheeler called this experiment delayed choice experiment.

We shall see that this experiment may have another explanation. This explanation is done in the framework of the modern nonlinear causal quantum physics based in the early ideas of de Broglie.

The conceptual Wheeler's experiment was now put into practice by the Paris group of Allan Aspect. In this beautiful experiment [2] the initial device of Wheeler, shown in Fig.1, was replaced by a Mach Zehnder interferometer, with arms of about 50m, and the photographic plate was replaced by a very ingenious device. An explanation about this ingenious device can be found in reference [2].

2. The Orthodox Quantum Mechanics

In the structure of the Orthodox Quantum Mechanics there is a fundamental relation between the conjugate variables γ and $\mathbf{k}'$. In the general case for the three dimensional $\mathbf{k}'$ space this relation is given by:

$$\psi(\boldsymbol{\gamma}) = \int \varphi(\mathbf{k}')\, e^{i\mathbf{k}'\cdot\boldsymbol{\gamma}}\, d^3k' \tag{2.1}$$

where $\boldsymbol{\gamma} = (\mathbf{r} - \mathbf{c}t)$ and $|\mathbf{k}'| = 2\pi/\lambda$ is the spatial frequency.

As can be inferred, this expression represents simply a linear superposition of plane waves. The infinite harmonic plane waves, that have a well defined frequency and consequently a well defined energy, are at the very basis of the non-locality and non-temporality of the theory. On the other hand, the same expression may also represent, by an adequate choice of the height coefficient function, a wave-packet describing the region where the probability of finding the quantum particle is non-null. In fact, if we choose the coefficient function $\varphi(\mathbf{k}')$, in the one dimensional case, as a gaussian distribution centred in k:

$$\varphi(k') = Ae^{-\frac{(k'-k)^2}{2\sigma_k^2}} \tag{2.2}$$

we have, after some simple calculations, the generally known solution:

$$\psi(x) = A'e^{-\frac{(x-ct)^2}{2\sigma_x^2}} e^{ik(x-ct)} \tag{2.3}$$

where $A' = \sqrt{2\pi} A\sigma_k$ and $\sigma_x \sigma_k = 1$.

3. Modern Wheeler’s delayed choice experiment

In Wheeler’s delayed-choice Gedanken Experiment, as is usual in this kind of experiments, only single photons enter the beamsplitter $\mathrm{BS}_{\mathrm{Input}}$. After crossing the Mach-Zehnder interferometer the photon arrives at the detectors D_1 or D_2 (see Fig. 2). The relationship between the reflection and transmission coefficients is the usual one and given by $R = r^2$ and $T = t^2$, with $R = T = 1/2$. Using as input the expression (2.3) for the wave-packet, representing the region where the photon can be localized, whose intensity is:

$$I_0 = |\psi|^2 = |A'|^2 e^{-\frac{(x-ct)^2}{\sigma_x^2}} \tag{3.1}$$

the total state in the interferometer is composed of two possibilities: 1) the open configuration; 2) the closed configuration. In either case the observation is realized in the detector D_1 or D_2, furthermore the two arms of the interferometer, corresponding to path 1 and path 2, have a relative phase shift of δ. Another detail of the experiment is that the two photons are linearly polarized therefore if they are perpendicular, that is, if they have a relative polarization of $\pi/2$, they won't interferer. With these considerations in mind the intensities observed at the detectors are given by:

$$
\begin{aligned}
I_{D_1} &= I_0/2\left[1-\cos(\Delta\eta)\cos(\delta)\right]\\
I_{D_2} &= I_0/2\left[1+\cos(\Delta\eta)\cos(\delta)\right]
\end{aligned}
\tag{3.2}
$$

where $\Delta\eta$ gives the angle of polarization between the two wave-packets.

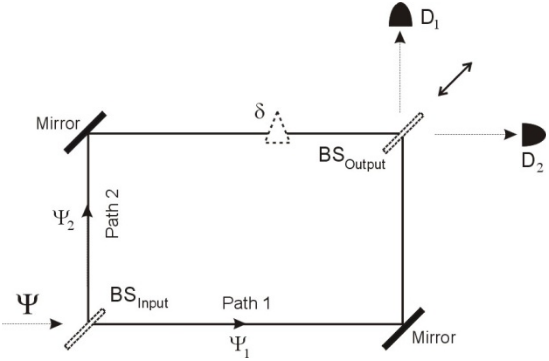

Fig. 2 – Sketch of the orthodox explanation of the Wheeler's delayed-choice Gedanken Experiment.

4. Interference of the Wave Packet in the Causal Approach

In the causal approach, the single-photon, described by the finite wave ϕ, enters the input beamsplitter BS_{input} and interacts with it through a nonlinear process (the Fig. 3 show one of the configurations of this experiment). Any quantum particle, namely the photon, is composed of a very localized complex structure ξ, initially called singularity and now renamed "acron", to avoid confusion with the mathematical terminology. This highly localized indivisible structure, the acron, contains almost all the energy of the particle. The particle is composed also of an extended yet finite part, the theta wave, θ, carrying a negligible quantity of energy. The acron [3], immersed in the theta wave field, is guided, according to the principle of eurhythmy [4], to the regions of space where the intensity of the wave is greater. Therefore, due to its extended nature, the theta wave upon arriving at the input beamsplitter is divided in two parts, each following along the arms of the interferometer. In what concerns the acron things are quite different. The acron ξ maintain its identity and follows only through one or the other of the two paths.

In the open configuration everything happens as if the beams do not mix at the output beamsplitter BS_{output}. Since the beams behave, for all practical purposes, as independent, the clicks at the detectors D_1 and D_2 are totally independent of the relative phase shift δ and thus reveal a pattern associated with the corpuscular behaviour of the quantum particle.

In the closed configuration, the beams do mix at the output beamsplitter BS_{output}. Therefore the propagation of the quantum particle ϕ is described exactly in the same way as before only now the two beams do indeed mix, therefore interfere. The acron follows immersed in one of the other output theta waves according to their respective intensities. The intensity of the output waves depends on the relative phase shift between the waves θ' and θ'' as is verified by the counts registered at the detectors. In this simple way the experiment is explained in a causal and objective form.

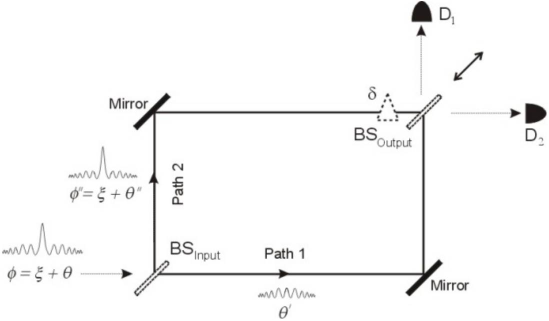

Fig. 3 – Sketch of the causal explanation of the Wheeler's delayed-choice Gedanken Experiment.

A solution of the nonlinear master Schrödinger equation [5] is the theta wave represented by a gaussian or Morlet wavelet:

$$\theta(x,t) = Ae^{-\frac{(x-ct)^2}{2\sigma_0^2}} e^{ik(x-ct)} \tag{4.1}$$

It can be easily seen that from the strict mathematical point of view the causal expression (4.1) is in all identical to the orthodox expression (2.3) obtained from a superposition of infinite harmonic plane waves. However its physical meaning is quite different. The expression (4.1) represents a real finite wave, localized in a region of approximate size σ_0, with a well defined energy.

In the general case, one assumes a propagation in the *x*-direction and the two linear polarized theta waves making angles η' and η'' with respect the axis *z* and *y*. The relation between the two general polarization vectors, $\hat{\mathbf{e}}'$ and $\hat{\mathbf{e}}''$, and the axis *z* and *y*, where $\hat{\mathbf{i}}$ and $\hat{\mathbf{j}}$ are unitary vectors, is given by:

$$\hat{\mathbf{e}}' = \hat{\mathbf{i}}\cos\eta' + \hat{\mathbf{j}}\sin\eta' \qquad \hat{\mathbf{e}}'' = \hat{\mathbf{i}}\cos\eta'' + \hat{\mathbf{j}}\sin\eta'' \tag{4.2}$$

With these considerations in mind, the total wave Θ_{D_1} arriving at the detector D_1 and its intensity I_{D_1} are given by:

$$\Theta_{\mathrm{D}_1} = rr\,\theta\, e^{i\pi} e^{i\delta}\hat{\mathrm{e}}' + tt\,\theta\,\hat{\mathrm{e}}''$$
$$I_{\mathrm{D}_1} = \frac{I_0}{2}\left[1 - \cos(\eta' - \eta'')\cos(\delta)\right] \tag{4.3}$$

where I_0 is given by the formula (3.1) and $\sigma_x = \sigma_0$. In the same way, the theta wave that arrives at the detector D_2 and its intensity I_{D_2} are given by:

$$\Theta_{\mathrm{D}_2} = tr\,\theta\, e^{i\pi/2} e^{i\delta}\hat{\mathrm{e}}' + rt\,\theta\, e^{i\pi/2}\hat{\mathrm{e}}''$$
$$I_{\mathrm{D}_2} = \frac{I_0}{2}\left[1 + \cos(\eta' - \eta'')\cos(\delta)\right] \tag{4.4}$$

From expressions (4.3) and (4.4) we see that $I_0 = I_{\mathrm{D}_1} + I_{\mathrm{D}_2}$. It can also be seen that when the two theta waves are orthogonally polarized, then $\eta' - \eta'' = \pi/2$ (open configuration). There is no dependence on the change of the phase shift, meaning that there is not interference. In this case, the intensity in the detectors, D_1 or D_2, is always $I_0/2$, no matter what the value of the relative phase shift between the waves is. Finally, in the closed configuration $\eta' - \eta'' = 0$, there is an interference between the two real theta waves. In this case, as expected, the intensity pattern dependents in fact of the relative phase shift:

$$I_{\mathrm{D}_1} = \frac{I_0}{2}\left[1-\cos(\delta)\right] \qquad I_{\mathrm{D}_2} = \frac{I_0}{2}\left[1+\cos(\delta)\right] \tag{4.5}$$

A last point to mention is that while each harmonic plane wave in (2.1) occupies all space and time, the wavelet is a more general mathematical object. It can be seen, e. g., from the formula (4.1) that Morlet's wavelet depends on the parameter σ_0 and, specifically, if one makes $\sigma_0 \to \infty$, then it transforms itself, as a particular case, into a harmonic plane wave.

5. Conclusion

In their article conclusion [2] the authors argued that their "realization of the Wheeler's delayed-choice Gedanken Experiment demonstrates beyond any doubt that the behavior of the photon in the interferometer depends on the choice of the observable which is measured, even when that choice is made at a position and a time that is separated from the entrance of the photon in the interferometer by a space-like interval". Supported by this argument, the authors declare "that Nature behaves in agreement with the predictions of Quantum Mechanics".

In our view, this conclusion is inconsistent and unfounded.

On one hand, the separability between the entrance of the photon in the interferometer and the choice of the observable made by the Quantum Random Number Generator (QRNG) relies, ultimately, on the assumption that superluminal signals (signals with a velocity v>c) do not have physical existence. But this is a very problematic assumption, because as is well known, in Orthodox Quantum Mechanics, in general, it is not possible to attribute to a quantum particle not observed (one "unobserved" quantum particle) neither a well determined velocity, neither a well determined position. Potentially, a quantum particle can have any velocity. Then in what is strictly concerns Quantum Mechanics, the “no v>c” assumption is truly meaningless. In reality, this assumption only makes sense in Relativity. It’s a Relativity assumption, not Quantum Mechanics one. And arguing about Quantum Mechanics validity by making Relativity assumptions seems at least a little obscure and fallacious. Especially because in the end this may even lead us to the odd conclusion that Quantum Mechanics is legitimized by Relativity theory.

On the other hand, in Orthodox Quantum Theory any quantum object is represented by a linear sum of harmonic plane waves. These waves are defined in the whole space and time, and they have constant amplitude everywhere. So, in terms of Orthodox Quantum Theory, any quantum object is a combination of space and time infinite waves. Consequently, in this approach, any quantum object somehow occupies the whole space and time. Then, by a logic consequence, it is impossible to have two truly separated quantum objects since necessarily any quantum object is composed by the same harmonic plane waves. This is the argument implicitly used by the Orthodox Quantum Theory interpretation to explain the classic case of measurements of quantum objects in entangled states. But this argument is also valid in the Orthodox interpretation even if they are not in “entangled” states. See, for instance, nonlocal and nontemporal interference experiments, like Franson-type ones [6], [7] and [8].

For these reasons it is meaningless to speak about space-time separability of quantum objects in the Orthodox Quantum Theory context. And consequently, the author’s conclusions are in fact the very premises, i.e., that Orthodox Quantum Mechanics is a nonlocal and holistic theory.

As has been shown, this experiment does not necessarily demonstrate that the behavior of the photon in the interferometer depends on the choice of the observable which is measured (and, for that reason, that Nature behaves like Orthodox Quantum Mechanics predicts, as argued by the authors). In particular, it is possible to explain the same results using a de Broglie-type approach.

As a final comment we wish to stress our surprise to see some highly skilled experimental physicists loosing their time with experiments that are completely irrelevant to the controversy concerning the foundations of Quantum Mechanics. It’s sad to see these experimental physicists doing something similar to the Aristotelians when they throw stones up vertically to “prove” that the Earth was static. Giordano Bruno [9] and Galileo [10] needed to give arguments and examples to show the irrelevance of those kinds of experiments, because the expected result if they adopt either the Copernican system or the Ptolemaic system, would be exactly the same.

Wheeler’s type of experiments are totally irrelevant as well. The expected result within Bohr’s interpretation, or within the Louis de Broglie interpretation of the quantum formalism, is precisely the same. However, the explanation behind the phenomenon is completely different as we have just shown in this paper.

There are in the scientific literature proposals of experiments that are not irrelevant to the conflict between the two previous mentioned interpretations of Quantum formalism [11]. Why not do them instead?

References

[1] J. A. Wheeler, *Delayed choice experiments*, in Proceedings of New Orleans Conference on the Mathematical Foundations of Quantum Theory, ed. A. Marlow, Academic Press, (New York, 1978); J. A. Wheeler, in Quantum theory and measurement, Ed. J. A. Wheeler and W. H. Zurek, (Princeton University Press) 1984, pp. 182-213;

[2] V. Jacques, E. Wu, F. Grosshands, F. Treussart, P. Grangier, A. Aspect and J-F. Roch, *Experimental realization of Wheeler’s delayed-choice gedanken experiment*, arXiv:quant-ph/0610241V1 28 October 2006;

[3] The Greek name acron, meaning the higher summit was suggested to us by the Portuguese Philosopher, Professor Eduardo Chitas;

[4] J. R. Croca, *The Principle of Eurhythmy a Key to the Unity of Physics* at the First Lisbon Colloquium for the Philosophy of Science - Unity of Science, Non traditional Approaches, Lisbon, October, 25-28, 2006.

[5] J. R. Croca, *Towards a nonlinear quantum physics*, World Scientific, London, 2003;

[6] J.D. Franson, Phys.Rev. A 44 (1991) 4552;

[7] H. Kaiser, R. Clothier, S. A. Werner, H. Rauch and H. Wölwitsch, *Phys. Rev. Lett.*, **67**, 6, (1991), pp. 683-686;

[8] H. Kaiser, R. Clothier, S. A. Werner, H. Rauch and H. Wölwitsch, *Phys. Rev. A.*.,**45**, 1, (1991), pp. 31-42;

[9] in his work "Cena delle ceneri" (1584);

[10] in his work "Dialogo sopra i due massimi sistemi del mondo. Tolemaico e copernicano" (1632) (Secunda Giornata);

[11] J. R. Croca, R. Moreira and A. J. Rica da Silva, in Causality and Locality in Modern Physics, Eds. G. Hunter et al. Kluwer Academic Publishers, 1998;