Non-locality and the Symmetrized Quantum Potential

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Abstract

Quantum non-locality can be difficultly understood and explained starting from the idea that the space-time manifold characteristic of special relativity is a fundamental entity: it is due to a quantum potential which is equivalent to a space-like, instantaneous action between the particles into consideration. In virtue of the features of quantum potential, a new order must be introduced to understand quantum phenomena, in particular quantum non-locality. One can say that in this new order subatomic particles are instantaneously connected through space which functions as an immediate information medium between them. Since to interpret in a correct and appropriate way also the time-reverse of a quantum process (and thus also of the instantaneous communication between subatomic particles) a symmetry in time in quantum mechanics is needed, a symmetrized reformulation of bohmian mechanics is introduced and analyzed.

French Abstract

La non-localité quantique peut être difficilement comprise et expliquée en partant de l'idée que la variété caractéristique de l'espace-temps de la relativité spéciale est une entité fondamentale; elle est due à un potentiel quantique qui est équivalent à une action instantanée de type spatial entre les particules considérées. En vertu des caractéristiques du potentiel quantique, un nouvel ordre doit être introduit afin de comprendre les phénomènes quantiques, en particulier, la non-localité quantique. On peut dire que dans ce nouvel ordre, les particules subatomiques seront instantanément reliées à travers l'espace qui fonctionne comme un médiateur immédiat d'information entre elles. Vu que pour pouvoir interpréter de manière correcte et appropriée aussi le temps inversé d'un procédé quantique, (et par conséquence aussi la communication instantanée entre les particules subatomiques), on a besoin d'une symétrie du temps dans la mécanique quantique, une reformulation symétrisée de la mécanique de Bohm est introduite et analysée.

Key words: non-locality, physical space, quantum potential, time symmetry, simmetrized quantum potential

1. Introduction

Quantum mechanics is the fundamental theory of natural phenomena. However, despite its incredible successes on the predictive point of view, this theory is plagued by several problems of interpretation as regards what it says about the world [1]. There are aspects of this theory which make it seem exotic and mysterious, far away from common sense. Among them, the most surprising aspect is certainly represented by quantum non-locality and entanglement, by the non separability of subatomic particles.

To be explicit and illustrate quantum non locality, let us consider an example given by Bohm [2] in 1951, in which we have a physical system given by a molecule of total spin 0 composed by two spin ½ atoms in a singlet state: $\psi(\vec{x}_1,\vec{x}_2) = f_1(\vec{x}_1)f_2(\vec{x}_2)\frac{1}{\sqrt{2}}(u_+v_- - u_-v_+)$ (1),

where $f_1(\vec{x}_1)$, $f_2(\vec{x}_2)$ are non-overlapping packet functions. Here $u_\pm$ are the eigenfunctions of the spin operator $\hat{s}_{z_1}$ in the z-direction pertaining to particle 1 and, in analogous way, $v_\pm$ are the eigenfunctions of the spin operator $\hat{s}_{z_2}$ in the z-direction pertaining to particle 2: $\hat{s}_{z_1}u_\pm = \pm\frac{\hbar}{2}u_\pm$, $\hat{s}_{z_2}v_\pm = \pm\frac{\hbar}{2}v_\pm$. Given such a state, suppose we perform a spin measurement on system 1 in the z-direction and that we obtain the result spin up. Then, according to the usual quantum theory, the wave function (1) reduces to the first of its summands:

$\psi \to f_1 f_2 u_+ v_-$ (2).

As a result, the final wave function is factorizable and we know the state of the unmeasured system 2, namely v_- which indicates that the system 2 has spin down. But this outcome depends on the kind of measurement carried out on particle 1. By performing different types of measurement on atom 1 we will bring about distinct states of the atom 2, and this means that as regards spin measurements there are correlations between the two atoms. Although the two partial systems (the atom A and the atom B) are clearly separated in space (in the conventional sense that the outcomes of position measurements on the two systems are widely separated), indeed they cannot be considered physically separated because the state of the atom 2 is instantaneously influenced by the kind of measurements made on the atom 1. Bohm's example shows clearly that entanglement in spin space implies non-locality and non-separability in Euclidean three-dimensional space: this comes about because the spin measurements couple the spin and space variables.

2. Quantum non-locality and bohmian quantum potential

Quantum non-locality can be easily explained in the context of Bohm's version of quantum mechanics. In de Broglie-Bohm's pilot wave theory the non-local correlations concerning microscopic phenomena are tied to the action of a new form of potential, the quantum potential.

In his classic works of 1952 and 1953 [3],[4] Bohm showed that if we interpret each individual physical system as composed by a corpuscle and a wave guiding it, the movement of the corpuscle under the guide of the wave happens in agreement with a law of motion which assumes the following form

$$\frac{\partial S}{\partial t}+\frac{|\nabla S|^2}{2m}-\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}+V=0 \quad (3)$$

(where *R* is the amplitude and *S* is the phase of the wave function, $\hbar$ is Planck's reduced constant, *m* is the mass of the particle and *V* is the classic potential). This equation is equal to the classical equation of Hamilton-Jacobi except for the appearance of the additional term

$$Q=-\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R} \quad (4)$$

having the dimension of an energy and containing Planck constant and therefore appropriately defined quantum potential. The equation of motion of the particle can be expressed also in the form

$$m\frac{d^2\vec{x}}{dt^2}=-\nabla(V+Q) \quad (5),$$

thus equal to Newton's second law of classical mechanics, always with the additional term *Q* of quantum potential. The movement of an elementary particle, according to Bohm's pilot wave theory, is thus tied to a total force which is given by the sum of two terms: a classical force (derived from a classic potential) and a quantum force (derived just from the quantum potential)[(5),(6)]. Equations (3) and (5) could give the impression that we have a return to a classical account of quantum processes. However, this is not the case.

Central in order to understand the features of bohmian mechanics is the appearance of the quantum potential. If we examine its form, we may note that it does not have the usual properties expected from a classic potential. Relation (4) tells us clearly that the quantum potential depends on how the amplitude of the wave function varies in space. The presence of Laplace operator indicates that the action of this potential is like-space, namely creates onto the particle a non-local, instantaneous action. The appearance of the amplitude of the wave function in the denominator also explains why the quantum potential can produce strong long-range effects that do not necessarily fall off with distance and so the typical properties of entangled wave functions. Thus even though the wave function spreads out, the effects of the quantum potential need not necessarily decrease. This is just the type of behaviour required to explain the EPR paradox.

If we examine the expression of the quantum potential in the two-slit experiment, we find that it depends on the width of the slits, their distance apart and the momentum of the particle. In other words, it has a contextual nature, namely brings a global information on the process and its environment. It contains an instantaneous information about the overall experimental arrangement. Moreover, this information can be regarded as being active in the sense that it modifies the behaviour of the particle. In a double-slit experiment, for example, if one of the two slits is closed the quantum potential changes, and this information arrives instantaneously to the particle, which behaves as a consequence.

Now the fact that the quantum potential produces a like-space and an active information means that it cannot be seen as an external entity in space but as an entity which contains a spatial information, as an entity which represents space. On the basis of the fact that the quantum potential has an instantaneous action and contains an active information about the environment, one can say that it is space the medium responsible of the behaviour of quantum particles. Considering the double-slit experiment, the information that quantum potential transmits to the particle is instantaneous just because it is a spatial information, is linked to physical space.

It is also important to underline that in the standard interpretation of quantum mechanics the non-locality of quantum processes is an unexpected host and often does not receive the adequate attention. On the other hand, Bohm was the first to put in evidence in a clear way the origin of quantum non-locality. Bohm's theory manages to make manifest this essential feature of quantum mechanics, just by means of the quantum potential. In particular, taking into consideration a many-body system, Bohm's theory shows clearly that the quantum potential acting on each particle is a function of the positions of all the other particles and thus in general does not decrease with distance. As a consequence, the contribution to the total force acting on the *i*-th particle coming from the quantum potential, i.e. $\nabla_i Q$, does not necessarily fall off with distance and indeed the forces between two particles of a many-body system may become stronger, even if $|\psi|$ may decrease in this limit. The equation of motion of the *i*-th particle in the limit of big separations assumes the form

$$m_i \frac{\partial^2 \vec{x}_i}{\partial t^2} = -\left[\nabla_i Q(\vec{x}_1, \vec{x}_2, ..., \vec{x}_n) + \nabla_i V_i(\vec{x}_i)\right] \quad (6)$$

and thus depends on the coordinates of all the n particles of the system: this determines just non-local correlations in a many-body system. In virtue of the features of the quantum potential, Bohm's theory turns out to be intrinsically olistic, in which "the whole is more than the sum of the parts". It is a merit of the pilot wave theory to show in such a direct way this property that, according to Bohm, "… is the newest and most fundamental ontological characteristic implied by quantum theory"[(7)].

The appearance of non-separability and non-locality in the Bohm approach led Bell to his famous inequalities[(8)]. Of course non-locality is not a feature that fits comfortably with the mechanical paradigm, but it was this feature that led Bohm to the conclusion that his approach was not mechanical. In this regard more details can be found in Bohm and Hiley (1993)[(9)].

Detailed investigations into these questions in the Bohm approach and in the review of other approaches to quantum mechanics led to the idea that the Cartesian order could no longer be used to explain quantum processes, in particular quantum non-locality. What is needed is a radically new order in which to understand quantum phenomena.

In this regard, already in 1960 Geoffrey Chew[(10)] pointed out that there is no necessity to explain quantum processes on the basis of the space-time manifold. This consideration of Chew appears legitimate if it is applied to the interpretation of EPR-type experiments. One encounters problems in explaining the instantaneous communication between subatomic particles if assumes that space-time is a fundamental entity. If space-time is assumed as primary, then, ipso facto, locality should be absolute. Instead quantum particles show non-local correlations.

In 1980 Bohm suggested that the new order in which to understand quantum phenomena would be based on process and called this new order the implicate order: the quantum potential must be considered an active information source linked to a quantum background, namely just the implicate order. The intention behind the introduction of this new order was simply to develop new physical theories together with the appropriate mathematical formalism that will lead to new insights into the behaviour of matter and ultimately to new experimental tests.

Following this research line, Hiley recently suggested that quantum processes evolve not in space-time but in a more general space called pre-space, which is not subjected to the Cartesian division between res extensa and res cogitans. In this view, the space-time of the classical world would be some statistical approximation and not all quantum processes can be projected into this space without producing the familiar paradoxes, including non-separability and non-locality [11]. According to Hiley's research, quantum domain is to be regarded as a structure or order evolving in space-time, but space-time is to be regarded as a higher order abstraction arising from this process involving events and abstracted notions of space or space-like points [12]. These points are active in the sense that each point is a process that preserves its identity and its incidence relations with neighbouring points. Thus points themselves are not static concepts, but part of the underlying process. In 1993 Hiley and Monk showed that this could be realized in a very simple algebraic structure, namely the discrete Weyl algebra [13]. According to Hiley, process must be taken as fundamental while space-time, fields and matter can be derived from this basic process on the basis of the idea that process is describable by elements of an algebra and the relevant structure process is defined by the algebra itself. In particular, Hiley used the sympletic Clifford algebra which can be constructed from boson annihilation and creation operators. This algebra contains the Heisenberg algebra, suggesting thus it will strongly feature in a process orientated approach to quantum theory. It was these possibilities that led Hiley and Monk in 1993 to explore a simpler finite structure, the discrete Weyl algebra.

In synthesis, the basic underlying assumption of Hiley's general approach is that the ontology is based on a process that cannot be described explicitly. It can only be described implicitly, hence the terminology "implicate order". This implicate order is a structure of relationships and is not some woolly metaphysical construction, it is a precise description of the underlying process, mathematically expressed in terms of a non-commuting algebra. This process allows partial views because nature is basically participatory.

The considerations of Chew, the research of Bohm and Hiley clearly show the legitimacy to understand and explain quantum non-locality on the basis of approaches different from the space-time manifold. The space-time manifold characteristic of special relativity cannot be considered as basic and fundamental because does not seem compatible with the instantaneous communication between subatomic particles. Here, in virtue of the peculiar characteristics of quantum potential, we suggest therefore the idea that bohmian implicate order (or analogously Hiley's pre-space and notion of underlying process of quantum phenomena) can be assimilated to the idea of physical space as an immediate information medium.

The features of quantum potential imply that space has clearly an important role in determining the motion of a subatomic particle. On the basis of the formula (4), one can say that it is space the medium responsible of the behaviour of quantum particles. One can say that the quantum potential (4) contains the idea of space as an immediate information medium in an implicit way.

In other words, when one takes into consideration an atomic or subatomic process (such as for example the case of an EPR-type experiment, of two subatomic particles, before joined and then separated and carried away at big distances one from the other), physical space assumes the special "state" represented by quantum potential, and this allows an instantaneous communication between the particles into consideration [14]. If we take under examination the situation considered by Bohm in 1951 (illustrated in chapter 1) we can say that it is the state of space in the form of the quantum potential which produces an instantaneous connection between the two particles as regards the spin measurements: by disturbing system 1, system 2 may indeed be instantaneously influenced despite the big distance separating the two systems thanks to the features of space which put them in an immediate communication.

Therefore, space allows us to explain why and in what sense, in an EPR experiment, two particles coming from the same source and which go away, remain joined by a mysterious link, why and in what sense if we intervene on one of two particles A and B, also the other feels the effects instantaneously despite the relevant distances separating it. In virtue of the features of quantum potential, the instantaneous connection between two quantum particles also when they are at big distance can be seen as an effect of space. Information does not travel between particle A and particle B, information between particle A and particle B has not speed: by means of the quantum potential, space itself is informing particle A about the behaviour of particle B and opposite [15] .

In synthesis, one can say that in EPR experiment quantum potential makes physical space an “immediate information medium” between elementary particles. In EPR experiment the behaviour of a subatomic particle is influenced instantaneously by the other particle thanks to space which functions as an immediate information medium; the information between the two particles is instantaneously transmitted by space. Through the action of quantum potential physical space keeps two elementary particles in an immediate contact.

3. A time-symmetric formulation of bohmian quantum mechanics

According to the interpretation proposed in the previous chapter, the instantaneous, non local communication between two quantum particles can be seen as a consequence of the fact that the information between the two particles has not speed, that physical space assumes the role of a direct, immediate information medium between them (in the form of the quantum potential). Moreover, it is important to underline that the instantaneous communication between two particles in an EPR-type experiment is characterized by a sort of symmetry: it occurs both if one intervenes on one particle and if one intervenes on the other, in both cases the same type of process happens and always thanks to space which functions as an immediate information medium. Now, if we imagine to film the process of an instantaneous communication between two subatomic particles backwards, namely inverting the sign of time, we should expect to see what really happened. Inverting the sign of time, there is however no guarantee that we obtain something that corresponds to what physically happens. It is true that the communication between the two particles is immediate, but the wave function of them depend in general also on time. However the standard quantum laws are not time-symmetric and therefore inverting the sign of time, the filming of the process could not correspond to what physically happens. Although the quantum potential (4) has a like-space, an instantaneous action, however it comes from Schrödinger equation which is not time-symmetric and therefore its expression cannot be considered completely satisfactory just because it can meet problems inverting the sign of time. Also the original bohmian approach, although allows us to explain quantum non-locality, cannot be considered completely convincing because it is not time-symmetric.

On the basis of these considerations, in order to interpret in the correct way, also in symmetric terms in the exchange of t in $-t$, the instantaneous communication between subatomic particles and thus in order to reproduce in the appropriate way the interpretation of physical space as an immediate information medium, in quantum theory in line of principle a symmetry in time is required. In this chapter we propose to introduce a new symmetrized version of quantum potential, able to explain a symmetric and instantaneous communication and therefore to represent a good candidate for the state of the physical space as an immediate information medium.

In this regard, let us start taking into consideration standard quantum mechanics. The standard interpretation of quantum mechanics is not time-symmetric. The asymmetry of the standard interpretation is somewhat evident in the Schrödinger equation itself

$$i\hbar\frac{\partial}{\partial t}\left|\psi(t)\right\rangle = H\left|\psi(t)\right\rangle \quad (7),$$

because the substitution $t \to -t$ yields a different equation. A more dramatic asymmetry concerns the collapse postulate; upon measurement, a wave function collapses to a pure state only in the forward-time direction. The time-reverse of this process is not permitted. The standard interpretation predicts therefore a dramatic disagreement between forward-time and reverse-time interpretation of the same physical event. This fact is evident also as regards EPR experiment and quantum non-locality. In fact, according to the standard interpretation the time-reverse of the process of instantaneous communication of two subatomic particles in EPR experiment could not correspond to what happens. Taking into account the considerations made in the previous chapter about the idea of space as a direct, immediate information medium between elementary particles, the fact that according to the standard version the time-reverse of the process of instantaneous communication of two subatomic particles is not interpreted in the correct way has an important consequence. In fact, one can deduce immediately that the standard interpretation of quantum mechanics cannot be considered compatible with the idea of physical space as a “direct information medium” between elementary particles. This fact provides an important motivation to search for an interpretation of quantum mechanics in which a forward-time and reversed-time perspective of the same physical events would be interpreted in the same manner and thus in which the idea of space as a direct information medium would be reproduced in the correct way. One can address this problem by taking into consideration the time-symmetric formulation of quantum mechanics recently developed by Wharton. Wharton’s model consists in applying two consecutive boundary conditions onto solutions of a time-symmetrized wave equation[16]. In synthesis, the proposal of Wharton is based on the following three postulates:

1. The wave function is no longer a solution of the Schrödinger equation, but instead is the solution $\left|C(t)\right\rangle$ to the time-symmetric equation

$$\begin{pmatrix} H & 0 \\ 0 & -H \end{pmatrix}\left|C(t)\right\rangle = i\hbar\frac{\partial}{\partial t}\left|C(t)\right\rangle \quad (8)$$

   where $\left|C(t)\right\rangle = \begin{pmatrix} \psi(t) \\ \phi(t) \end{pmatrix}$, $\psi(t)$ is the solution of the standard Schrödinger equation, $\phi(t)$ is the solution to the time-reversed Schrödinger equation.

2. Each measurement Q_M of a wave function (at some time t_0) imposes the result of that measurement as an initial boundary

condition on $\left|C_+\right\rangle = \left|\psi\right\rangle + T\left|\phi\right\rangle$, and as a final boundary condition on $\left|C_-\right\rangle = \left|\psi\right\rangle - T\left|\phi\right\rangle$ where T is the time-reversal operator. In other words, instead of a collapse postulate, this formulation imposes a boundary condition on the wave function at every measurement, equal to the outcome of that measurement.

3. Instead of the standard probability formula, the relative probability of any complete measurement sequence on a wave function $\left|C(t)\right\rangle$ at times $t_1, t_2, ..., t_n$ is

$$P_0 = \prod_{n=1}^{N-1} \left(C_-(t_n{}^+) \right)\left(C_+(t_n{}^+) \right)\left(C_+(t_{n+1}{}^-) \right)\left(C_-(t_{n+1}{}^-) \right) \quad (9)$$

where N>1 and each measurement is constrained by the boundary conditions $Q_M \left| C_\pm(t_0{}^\pm \right\rangle = q_n \left| C_\pm(t_0{}^\pm \right\rangle$.

This proposal of Wharton is an interesting attempt to build a fully time-symmetric formulation of quantum mechanics, without requiring a time-asymmetric collapse of the wave function upon measurement. Therefore it can be considered a starting-point in order to interpret in the correct manner both the forward-time and the reversed-time perspectives of the same physical event. In particular, it can be considered the starting point to interpret in the correct way the time-reverse process of the instantaneous communication of two particles in EPR-type experiments.

Now, since non-locality is due to bohmian quantum potential, to the like-space, instantaneous action of the quantum potential, in order to assure the symmetry in time needed to interpret also the time-reverse process in the correct manner and thus to find the most appropriate candidate for the state of space as a direct information medium between subatomic particles, we can reformulate the bohmian mechanics for the time-symmetric equation (8). In this regard, just like in the original bohmian theory, we decompose the time-symmetric equation (8) into two real equations, by expressing the wave functions ψ and ϕ in polar form:

$\psi = R_1 e^{iS_1/\hbar}$ (10),

$\phi = R_2 e^{iS_2/\hbar}$ (11)

where R_1 and R_2 are real amplitude functions and S_1 and S_2 are real phase functions. Inserting (10) and (11) into (8) and separating into real and imaginary parts we obtain the following equations for the fields R_1, R_2, S_1 and S_2. The real part gives

$$\frac{\partial}{\partial t}\begin{pmatrix} S_1 \\ S_2 \end{pmatrix} + \frac{1}{2m}\begin{pmatrix} (\nabla S_1)^2 \\ (\nabla S_2)^2 \end{pmatrix} - \frac{\hbar^2}{2m}\begin{pmatrix} \dfrac{\nabla^2 R_1}{R_1} \\ -\dfrac{\nabla^2 R_2}{R_2} \end{pmatrix} + \begin{pmatrix} V \\ -V \end{pmatrix} = 0 \quad (12)$$

and the imaginary part may be written in the form

$$\frac{\partial}{\partial t}\begin{pmatrix} R_1{}^2 \\ R_2{}^2 \end{pmatrix} + \nabla \cdot \begin{pmatrix} \dfrac{R_1{}^2 \nabla S_1}{m} \\ \dfrac{R_2{}^2 \nabla S_2}{m} \end{pmatrix} = 0 \quad (13).$$

We obtain in this way a symmetrized extension of bohmian mechanics which is characterized by a symmetrized quantum potential at two components of the form $Q = -\frac{\hbar^2}{2m}\begin{pmatrix} \frac{\nabla^2 R_1}{R_1} \\ -\frac{\nabla^2 R_2}{R_2} \end{pmatrix}$ (14)

where R_1 is the amplitude function of ψ and R_2 is the amplitude function of ϕ. The symmetrized quantum potential (14) can be considered the starting-point to have a symmetry in time in bohmian quantum mechanics. It provides a coherent description of the quantum world in the bohmian approach avoiding the dramatic disagreement between forward-time and time-reverse of the same physical process.

Let us examine now in more detail the form of this quantum potential. As one can easily see, just like the quantum potential of the original Bohm theory, also the symmetrized quantum potential (14) has an action which is stronger when the mass is more comparable with Planck constant, and Laplace operator indicates that the action of this potential is like-space, non-local, instantaneous. The difference from the original bohmian mechanics lies in the fact that (14) has two components, namely depends also on the wave function concerning the time-reverse process, and therefore its space-like, non-local, instantaneous action is predicted not only by the forward-time process but also by the time-reverse process (and this implies therefore that the process of the instantaneous action between two subatomic particles can be interpreted in the correct way also exchanging *t* in –*t*). More precisely, if we analize the mathematical expression of the symmetrized quantum potential (14) we can make the following important considerations. The first component, $Q = -\frac{\hbar^2}{2m}\frac{\nabla^2 R_1}{R_1}$, indicates that in the forward-time process the action of the quantum potential on the particle under consideration is instantaneous, space-like; the second component, $Q = -\frac{\hbar^2}{2m}\frac{\nabla^2 R_2}{R_2}$, allows us to reproduce in the correct way also the time-reverse of the process of the instantaneous action of the quantum potential on that particle.

Moreover, it is important to underline that the symmetrized quantum potential has a crucial role inside the mathematical formalism of the theory. In fact, in analogy to what happens in bohmian original theory, in the symmetrized extension the symmetrized quantum potential (14) must not be considered a term ad hoc. It plays a fundamental role in the symmetrized quantum formalism: in the formal plant of the symmetrized Bohm's theory it emerges directly from the symmetrized Schrödinger equation. Without the term (14) the total energy of the physical system would not be conserved. In fact, equation (12) can also be written in the equivalent form

$$\frac{1}{2m}\begin{pmatrix} (\nabla S_1)^2 \\ (\nabla S_2)^2 \end{pmatrix} - \frac{\hbar^2}{2m}\begin{pmatrix} \frac{\nabla^2 R_1}{R_1} \\ -\frac{\nabla^2 R_2}{R_2} \end{pmatrix} + \begin{pmatrix} V \\ -V \end{pmatrix} = -\frac{\partial}{\partial t}\begin{pmatrix} S_1 \\ S_2 \end{pmatrix} \quad (15),$$

which can be seen as a real energy conservation law for the forward-time and the reverse-time process in symmetrized quantum mechanics: here one can easily see that without the quantum potential

$$Q = -\frac{\hbar^2}{2m}\begin{pmatrix} \frac{\nabla^2 R_1}{R_1} \\ -\frac{\nabla^2 R_2}{R_2} \end{pmatrix} \quad (14)$$

energy would not be conserved. Equation (15) tells us also that the reverse-time of a physical process is characterized by a classic potential and a quantum potential which are endowed with an opposed sign with respect to the corresponding potentials characterizing the forward-time process.

It is also interesting to observe that inside this time-symmetric extension of bohmian mechanics the correspondence principle becomes

$$-\frac{\hbar^2}{2m}\begin{pmatrix} \frac{\nabla^2 R_1}{R_1} \\ -\frac{\nabla^2 R_2}{R_2} \end{pmatrix} \to \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad (16).$$

In this classical limit we have the classical Hamilton-Jacobi equation at two components:

$$\frac{\partial}{\partial t}\begin{pmatrix} S_1 \\ S_2 \end{pmatrix} + \frac{1}{2m}\begin{pmatrix} (\nabla S_1)^2 \\ (\nabla S_2)^2 \end{pmatrix} + \begin{pmatrix} V \\ -V \end{pmatrix} = 0 \quad (17)$$

which shows us just that the time-reverse of the classical process involves a classic potential which is endowed with an opposed sign with respect to the classic potential characterizing the forward-time process.

Moreover, following the idea originally proposed by Bohm and Hiley in 1984, also the quantum potential (14) can be interpreted as a sort of “information potential”: the particles in their movement are guided by the quantum potential just as a ship at automatic pilot can be handled by radar waves of much less energy than that of the ship and this concerns also the time-reverse of this process in the sense that also the time-reverse of this process reproduces what happens as regards the transmission of the information. On the basis of this interpretation, the results of double-slit experiment are explained by saying that the quantum potential (14) contains an active information, for example about the slits, and that this information manifests itself in the particles’ motions and the time-reverse of these motions can be explained in the same, correct way, namely through the idea of the active information.

In the case of a many-body system constituted by N particles the symmetrized quantum potential becomes

$$Q = \sum_{i=1}^{N} -\frac{\hbar^2}{2m_i}\begin{pmatrix} \frac{\nabla_i^2 R_1}{R_1} \\ -\frac{\nabla_i^2 R_2}{R_2} \end{pmatrix} \quad (18).$$

The symmetrized quantum potential (18) can explain quantum non-locality in many-body systems in the correct way (namely also taking into consideration the time-reverse process): it reproduces the fact that the communication between subatomic particles is instantaneous and allows us to interpret in the correct way also the time-reverse of the process of this instantaneous communication. More precisely, the first component, $Q = \sum_{i=1}^{N} -\frac{\hbar^2}{2m_i}\frac{\nabla_i^2 R_1}{R_1}$, explains the instantaneous communication between subatomic particles in many-body systems in the forward-time; the second component, $Q = \sum_{i=1}^{N} -\frac{\hbar^2}{2m_i}\frac{\nabla_i^{\,2} R_2}{R_2}$, allows us to reproduce in the correct way the time-reverse of this instantaneous communication. According to the authors' point of view, this formula (18) can be considered the starting point to develop mathematically the interpretation of space as an immediate information medium between elementary particles. In other words, we can consider equation (18) as the most adequate candidate to present in the correct way the idea of space as a direct information medium between elementary particles. It is the quantum potential (18) which can be considered the most satisfactory candidate to represent the "special state of physical space in the presence of microscopic processes" for many-body systems.

4. Conclusions

The space-time manifold of special relativity cannot be considered primary and fundamental in order to understand and explain quantum processes, in particular quantum non-locality. A new order is necessary which must take into account that non-locality is well explained by the like-space action of quantum potential. One can therefore introduce the idea that the instantaneous communication between subatomic particles is linked to space which functions as an immediate information medium. The most adequate candidate to represent mathematically the idea of space as an immediate information medium appears to be the symmetrized quantum potential. In the presence of subatomic particles, space assumes the special state represented by the symmetrized quantum potential which produces an instantaneous communication between them and allows us to interpret in a correct and appropriate way both the forward-time and the time-reverse of the same physical process.

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