The symmetrized quantum potential and space as a direct information medium

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ABSTRACT. According to significant theoretical results (regarding state space, Hamiltonian mechanics and quantum gravity for example) and experimental results (regarding immediate physical phenomena) the stage of the physical world is a timeless space and clock/time provides only a measuring system of the numerical order of material changes. This insight introduces interesting perspectives in the interpretation of quantum non-locality : subatomic particles move into space only and are instantaneously connected through space which functions as an immediate information medium between them. Since non-locality is due to bohmian quantum potential, and since to interpret in a correct 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 considered and analyzed. Finally, a symmetrized reformulation of Wheeler-De Witt equation is taken into examination which shows that also in the quantum gravity domain the idea of space as a direct information medium can be embedded.

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1 Introduction

The results of several authors suggest that time as human experiences it has not an objective existence. Already in 19^{th} century Ernst Mach said : “It is utterly beyond our power to measure the changes of things by time. Quite the contrary, time is an abstraction, at which we arrive by means of the changes of things". The idea of a timeless universe was then discussed by Einstein and Gödel at the beginning of the '50 of the last century. Gödel and Einstein opened new perspectives regarding definition and experience of time. They have been discussing the possibility that there is no time in the universe as science experiences it, that time into which material changes run exists only as a concept of our mind. In 1949, Gödel postulated also a theorem that stated : "In any universe described by the theory of relativity, time cannot exist" [1]. Today, the idea that physical time cannot be considered as a primary physical reality is receiving indeed more and more attention. For example, Woodward argues that Mach's principle leads to the conclusion that time, as we normally treat it in our common experience and physical theory, is not a part of fundamental reality [2]. Rovelli proposes the idea that time is not defined at the fundamental level (at the Planck scale), namely that, in the quantum gravity regime, time should be simply forgotten, that the concept of absolute time t, as used in Hamiltonian mechanics as well as in Schrödinger quantum mechanics, is not relevant in a fundamental description of quantum gravity [3, 4, 5]. As regards the view of time Julian Barbour says in *The Nature of Time* : "I will not claim that time can be definitely banished from physics ; the universe might be infinite, and black holes present some problems for the time picture. Nevertheless, I think it is entirely possible, indeed likely, that time as such plays no role in the universe" [6].

More and more current research is challenging with the view that space-time is the fundamental arena of the universe. In particular, some theoretical results show that the mathematical model of space-time does not correspond to a physical reality, and propose "state space" or "timeless space" as the arena instead. For example Palmer, in his recent paper entitled *A New Geometric Framework for the Foundations of Quantum Theory and the Role Played by Gravity*, suggests that, since quantum theory is inherently blind to the existence of such state-space geometries, attempts to formulate unified theories of physics within a conventional quantum-theoretic framework are misguided, and that a successful quantum theory of gravity should unify the causal non-Euclidean geometry of space time with the atemporal fractal geometry of state space [7]. Moreover, Girelli, Liberati and Sindoni have recently developed a toy model in which they have shown how the Lorentzian signature and a dynamical space-time can emerge from a non-dynamical Euclidean space, with no diffeomorphisms invariance built in. This toy-model provides an example where time (from the geometric perspective) is not fundamental, but simply an emerging feature [8]. In more detail, this model suggests that at the basis of the arena of the universe there is some type of "condensation", so that the condensate is described by a manifold R^4 equipped with the Euclidean metric $\delta^{\mu\nu}$. Both the condensate and the fundamental theory are timeless. The condensate is characterized by a set of scalar fields $\Psi_i\left(x_\mu\right)$, i=1,2,3. Their emerging Lagrangian L is invariant under the Euclidean Poincaré group ISO(4) and has thus the general shape

$$L = f\left(X_1\right) + f\left(X_2\right) + f\left(X_3\right); \quad X_i = \delta^{\mu\nu}\partial_\mu\Psi_i\partial_\nu\Psi_i \tag{1}$$

The equations of motion for the fields $\Psi_i\left(x_\mu\right)$ are simply given by

$$\partial_\mu\left(\frac{\partial L}{\partial X_i}\partial^\mu\Psi_i\right) = 0 = \sum_j\left(\frac{\partial^2 L}{\partial X_i\partial X_j}\left(\partial^\mu X_j\right) + \frac{\partial L}{\partial X_i}\partial_\mu\partial^\mu\Psi_i\right) \tag{2}$$

The fields $\Psi_i\left(x_\mu\right)$ can be expressed as $\Psi_i = \psi_i + \varphi_i$ where φ_i are the perturbations around the solutions ψ_i of the above equation.

Different choices of the solutions ψ_i lead to different metrics

$$g_k^{\mu\nu} = \frac{df}{dX_k}\left(\bar{X}_k\right)\delta^{\mu\nu} + \frac{1}{2}\frac{d^2 f}{\left(dX_k\right)^2}\left(X_k\right)\partial^\mu\psi_k\partial^\nu\psi_k \tag{3}$$

and the Lorentzian signature and the Minkowski metric can be obtained for the condition $\frac{df}{dX}(\bar{X}) + \frac{\alpha^2}{2}\frac{d^2f}{(dX)^2}(\bar{X}) < 0$, $\frac{df}{dX}(\bar{X}) > 0$.

The toy model developed by Girelli, Liberati and Sindoni shows that at a fundamental level space is a timeless condensate, that time as humans perceive it is only an emerging feature and that different solutions of the equations of motion of the fields characterizing this condensate determine different metrics of the space-time background. If in a timeless background different metrics are possible and time represents only an emerging feature, this means just that, at a fundamental level, time cannot be considered a primary physical reality, and thus that the duration of material changes has no existence of its own.

In line with the results of Palmer and Girelli, Liberati and Sindoni, in the recent article "The nature of time : from a timeless hamiltonian framework to clock time metrology" Prati has shown that Hamiltonian mechanics, both in the classical domain and in quantum field theory, is rigorously well defined without the concept of an absolute, idealized time and that in this timeless framework a physical system S, if complex enough, can be separated in a subsystem S2 whose dynamics is described, and another cyclic subsystem S1 which behaves as a clock [9]. An important result of Prati's research is that, as a consequence of the gauge invariance, a complex system can be separated in many ways in a part which constitutes the clock and the rest. This implies that the duration of material change provided by a cyclic subsystem cannot be considered a primary physical reality, that each subsystem which acts as clock provides only the numerical order of the dynamics of the other subsystem. More precisely, on the basis of Prati's model, by indicating with σ a parameter time which has the property of providing a privileged parameterization suitable for describing dynamics (σ is not an observable quantity) and introducing the set

$$\Omega\left(\sigma_A, \sigma_B\right) = \left\{\psi_2\left(\sigma\right) \in H_2/\sigma \in \left(\sigma_A, \sigma_B\right)\right\} \tag{4}$$

which is a particular set of states associates with the interval $(\sigma_A, \sigma_B))$, physical time as numerical order of the material motion of the system S2 can be defined mathematically as a counter function $t(n)$ that provides the number of states $\psi_2\left(\sigma\right) \in \Omega$ of the subsystem S2 whose dynamics is studied that satisfies an appropriate initial condition (namely the origin of measurement) $\psi_1\left(\sigma\right) = \bar{\psi}_1$ of the subsystem acting as a clock.

On the other hand, also from the point of view of the experimental results, we have important elements that indicate that, at a fundamental level, time exists only as a measuring system of the numerical order of material changes happening in a timeless space. In fact, for several physical events clock/time is zero, since no measurable time elapses for them to happen. These events can be appropriately defined as "immediate physical phenomena". If phenomena would happen in a temporal dimension intended as some physical reality, time could never be zero. Immediate physical phenomena have zero numerical order. In the quantum domain, examples of such phenomena are : the non-local correlations between quantum particles in EPR-type experiments and other immediate physical phenomena like tunneling or quantum entanglements regarding the continuous variable systems or the quantum excitations from one atom to another in Fermi's two-atom system [10, 11, 12, 13]. In quantum electrodynamics immediate phenomena are represented by the transmissions of interchange forces obeying the inverse square law (these are due to the exchange of space-like virtual photons). As regards this topic, J.H.

Field in his recent paper *Quantum electrodynamics and experiment demonstrate the nonretarded nature of electrodynamical force fields* showed that the intercharge force of the Møller scattering acts instantaneously : on the basis of the lowest order Feynman diagram, each virtual photon in the Møller scattering is both emitted and absorbed at the same instant, so that the corresponding force is transmitted instantaneously [14]. Moreover, this prediction regarding the space-like virtual photons of the Møller scattering has been verified in a recent experiment performed by A.L. Kholmetskii *et al.* in 2007 [15].

In synthesis, on the basis of several current theoretical and experimental research, one can conclude that the concept of space-time can be eliminated as a fundamental arena of physics and can be replaced with a timeless space where time exists only as a measuring system of material changes. In this article we will show that the idea of a timeless space as the fundamental arena of physics and, consequently, of time as a measuring system of the numerical order of material changes introduces interesting perspectives as regards the interpretation of quantum non-locality.

2 About the method to describe the motion of material objects

Let us consider a pendulum described by a variable P and let us swing it. In this situation, the experimentalist has got two physical objects : a pendulum, whose position is associated with the function P, and a clock. According to Newtonian mechanics, in order to study the motion of the pendulum we must consider the evolution of the variable P in the time measured by this clock which is assumed as an idealized quantity t. We must thus determine the function $P(t)$ of the variable P with respect to an idealized time : this function will be governed by an equation of motion of the form $\ddot{P} = -\omega P$, which has the solutions $P(t) = Asen\,(\omega t + \varphi)$. Moreover, the state of the pendulum at an arbitrary instant of the idealized time t can be characterized by its position and its speed. From these two boundary conditions, we can compute A and φ and therefore the function $P(t)$ at any t. But the crucial point is that, according to Newtonian mechanics, the time measured by the clock flows in an absolute way : it is intended as a primary physical quantity that passes uniformly without relation to anything external, and thus without reference to any change or way of measuring it. The clock is indeed considered just a devise to measure this idealized, absolute time and, therefore, from the point of view of Newtonian mechanics, the real dynamical system is composed by the pendulum alone.

On the other hand, as it has been rightly underlined by Rovelli, the same physical situation can be analyzed also from a different perspective, which according to the authors is more coherent with experimental facts. One can say that there is a physical system formed by the clock and the pendulum together and can view the dynamical system as expressing the relative motion of one with respect to the other. This is the perspective adopted by general theory of relativity : to express the relative motion of the variables, with respect to each other, in a democratic fashion [16].

In the example under consideration, if we adopt the point of view of pre-general relativistic physics, we describe the evolution of the pendulum with respect to a clock which is considered as a measuring system of an idealized time t that flows on its own in the universe, without reference to anything happens. Instead, in the context of general relativity, the clock must be considered itself a physical object and thus the equations of motion of the gravitational field associated with the pendulum and the clock must be taken into consideration. The gravitational field enters the equations of motion of the clock, the dynamics of the clock cannot be separated from the dynamics of gravity. From the point of view of general relativity, in order to predict the evolution in the physical clock time of the gravitational field, we have thus to consider the coupled gravity+clock dynamical system. As a consequence, in general relativity, physical time has to be identified with one of the degrees of freedom of the theory itself. Such a definition of time is often referred to as internal time. Thus, general relativity treats time in a peculiar way, as compared to pre-general relativistic physics. The absolute time t does not exist. It is replaced with different possible internal times, associated with specific physical clocks. Only the evolution with respect to these physical clocks makes sense.

Relativity of time in general theory of relativity is consistent with elementary perception. In stronger gravity clocks run slower than in weaker gravity. On the basis of elementary perception, one has no evidence that the motion of the pendulum occurs into an absolute time : one can conclude that the pendulum moves into space only and that the speed of its movement depends on the strength of gravitational field in the volume of space into consideration. With clocks one measures frequency, speed and numerical order of pendulum swinging. One can say that in general relativity there is not a preferred and observable quantity that plays the role of independent parameter of the evolution, just because clocks provide only a mathematical measure of the numerical order of physical events. Definition of time as "numerical order of material change" resolves in a clear way the problem concerning the interpretation of the physical clocks inside general relativity. Since clocks can be defined as those instruments which measure the speed of the material changes and movements, the internal clocks/times of general relativity are only measuring systems of the numerical order of material change. The definition of time as a mathematical coordinate that indicates the numerical order of material motion in space provides thus a clear and suggestive re-reading of the internal clocks/times of general relativity.

3 Physical time and mathematical time

One should distinguish between physical time (numerical order of material changes) and mathematical time (time as a parameter of physical theories). In order to clear better the distinction between physical time and mathematical time let us start with a question : "What is measured with a clock ?" On the basis of elementary perception (eyes) one can answer : "With a clock it is measured frequency, speed and numerical order of material changes". The smallest material change that can be observed in the universe is the motion of a photon through Planck distance. The unit of numerical order that describes this motion is called "Planck time". Planck time is the smallest unit to indicate the speed, frequency and numerical order of material changes.

For example, let us consider a photon that moves from a point A to a point B. Let us suppose that the distance between the point A and the point B is 100 Planck distances. The duration of the movement of this photon from A to B is described by a numerical order given by 100 units of Planck time. The photon does not move into time, it moves into space only. Time is a numerical order of this movement. We give this motion a sensation of duration by measuring it with a clock. With clock one measures speed, frequency and numerical order of motion of the photon from the point A to the point B [17].

As photon moves in space only and not in time in special theory of relativity the forth coordinate of space-time x_4 is an imaginary quantity : $x_4 = ict$. Here c is light speed, i is the imaginary number and t is a number that indicates the duration and numerical order of photon motion. The fourth imaginary coordinate is a mathematical coordinate with which we describe speed and numerical order of a photon motion into space that at the most fundamental level has a granular structure. In fact, taking into account the results of reticular space-time dynamics and loop quantum gravity, one can assume that quanta of space having the size of Planck length $l_p = \sqrt{\frac{\hbar G}{c^3}}$ are the fundamental constituents of space and, therefore, that Planck time $t_p = \sqrt{\frac{\hbar G}{c^5}}$ is the least unit of motion [18, 19].

In special theory of relativity the fourth coordinate $x_4 = ict$ of Minkowskian space-time is therefore different from the first three coordinates. To our knowledge, this fact does not yet receive an adequate attention. The first three coordinates constitute physical realities because they are numbers which correspond to the position of a material object in space. The fourth coordinate is instead only an imaginary number. It is used to describe the numerical order of events that run into three dimensional physical space. As a consequence, the space-time manifold of special relativity can be considered as a “physical-mathematical reality”.

On the other hand, the fourth coordinate $x_4 = ict$ of the Minkowskian arena, on the basis of its mathematical expression, is spatial too. Therefore, in the context of special relativity, it is more correct to imagine the cosmic space as a four-dimensional $4D$ space than as a $3D + T$ space-time manifold where the fourth dimension is a temporal dimension that flows on its own as an independent stage of the universe. Moreover, always as regards special relativity, Selleri has introduced general transformations of space and time between inertial reference frames that seem to indicate clearly that space and time must be considered as separate entities, that time must be separated from space [20, 21, 22]. Let a moving inertial system O’ observed from rest system O move with respect to the inertial system O with constant velocity $v < c$ parallel to the $x_1 = X$ axis. The transformation of the speed of clocks given by Selleri’s formalism

$$t' = \sqrt{1 - \frac{v^2}{c^2}} * t \tag{5}$$

shows clearly that the speed of the moving clock does not depend on the spatial coordinates but is linked only with the speed v of the inertial system O’. Equation (5) suggests clearly that the speed of the moving clock does not depend on the spatial coordinates but is linked only with the speed v of the inertial system O’ and thus that time is a distinct entity from space. As we have shown in our recent article *New Insights into Special Theory of Relativity*, time does not exist as a physical dimension into which material changes run. Time measured with clocks exists only as a numerical mathematical order of material changes (that occur in a timeless four-dimensional space) [23].

In general theory of relativity idea of time as a fourth coordinate of a physical reality called space-time allows hypothetical travel into time. Speculation of time travel into past leads into contradictions : one could travel into past and kill his ancestors. On the basis of the interpretation here proposed this contradiction is resolved. One can travel only into space and not into time because time exists only as a numerical order of events that run into space. Travelling into a temporal dimension that flows on its own as an independent variable of evolution is out of question. Here time is not considered to be an external medium in which life runs. Time is only a numerical order of change of life which runs in physical space. We are living in space only and not into an external temporal dimension that flows on its own [24].

4 EPR experiment, bohmian quantum potential and space as an immediate information medium

The idea of a physical space where time exists only as a numerical order of events (whose duration is a result of our measurement with clocks) throws new light in the explanation and interpretation of Einstein-Podolski-Rosen (EPR) experiment and thus of quantum nonlocality.

To illustrate EPR experiment, let us consider an example given by Bohm [25] in 1951, in which we have a physical system given by a molecule of total spin 0 composed by two spin $1/2$ atoms in a singlet state :

$$\psi(\vec{x}_1, \vec{x}_2) = f_1\left(\vec{x}_1\right) f_2\left(\vec{x}_2\right) \frac{1}{\sqrt{2}} \left(u_+ v_- - u_- v_+\right) \tag{6}$$

Here $f_1\left(\vec{x}_1\right)$, $f_2\left(\vec{x}_2\right)$ are non-overlapping packet functions, $u_\pm$ are the eigenfunctions of the spin operator $\hat{s}_{z_1}$ in the z-direction pertaining to particle 1 and $v_\pm$ are the eigenfunctions of the spin operator $\hat{s}_{z_2}$ in the z-direction pertaining to particle 2 : $\hat{s}_{z_1} u_\pm = \pm\frac{\hbar}{2} u_\pm$, $\hat{s}_{z_2} v_\pm = \pm\frac{\hbar}{2} v_\pm$. Let us suppose to perform a spin measurement on the particle 1 in the z-direction when the molecule is in such a state. And let us suppose moreover that we obtain the result spin up for this particle 1. Then, according to the usual quantum theory, the wave function (6) reduces to the first of its summands :

$$\psi \rightarrow f_1 f_2 u_+ v_- \tag{7}$$

The result of the measurement carried out on the particle 1 leads us to have knowledge about the state of the unmeasured system 2 : if the particle 1 is found in the state of spin up, we know immediately that the particle 2 is in the state v_- which indicates that the particle 2 has spin down. But this outcome regarding particle 2 depends on the kind of measurement carried out on particle 1. In fact, by performing different types of measurement on particle 1 we will bring about distinct states of the particle 2, and this means that as regards spin measurements there are correlations between the two particles. Although the two partial systems (the particle 1 and the particle 2) 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 particle 2 is indeed instantaneously influenced by the kind of measurements made on the particle 1. Bohm's example shows therefore 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.

Now, from the authors' point of view, the fact that the state of the particle 2 is instantaneously influenced by the kind of measurements regarding the particle 1 suggests that space assumes an important role in determining non-locality, that quantum non-locality is indeed determined by the medium of space. It is the medium of space 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 space which puts them in an immediate contact.

Quantum non-locality cannot be explained by invoking a mechanism of entities that are transmitters of information : there is no information signal in form of photon or some other particle traveling between particles 1 and 2 of Bohm's example. The time of information transfer between particle 1 and particle 2 is zero [26]. Information between particle 1 and particle 2 has not speed, has not duration : space itself is informing particle 1 about the behaviour of particle 2 and opposite. It is space the medium which 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 the two particles 1 and 2, also the other feels the effects instantaneously despite the relevant distances separating it [27]. It is space the fundamental entity which determines non-locality, which determines the instantaneous connection between two quantum particles also when they are at big distance.

In other words, one can say that in EPR experiment physical space is an "immediate information medium", a direct 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 the immediate medium of space. Moreover, if one imagines to exchange, to invert the roles of the two particles what happens is always the same type of process, namely an instantaneous communication between the two particles and the process can be always interpreted as the consequence of the fact that space acts as an immediate information medium between the particles under consideration.

It is important to underline that the idea of space as a direct, immediate information medium between subatomic particles must not be considered completely new inside physics. One can find the important role of space as the fundamental medium determining quantum non-locality already in the context of Bohm's original quantum potential approach (known also as de Broglie-Bohm pilot wave theory or bohmian version of quantum mechanics).

As it is known, in his classic works of 1952 and 1953 [28], rediscovering an interpretation already given by de Broglie at the 1927 Solvay congress [29], 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

$$\frac{\partial S}{\partial t} + \frac{|\nabla S|^2}{2m} - \frac{\hbar^2}{2m}\frac{\nabla^2 R}{R} + V = 0 \tag{8}$$

(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

$$Q = -\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R} \tag{9}$$

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

$$m\frac{d^2\vec{x}}{dt^2} = -\nabla(V + Q) \tag{10}$$

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 quantum potential) [30].

The equations of motion (8) and (10) of Bohm's pilot wave theory could give the impression that we have a return to a classical account of quantum processes. However, this is not the case in virtue of the appearance of the quantum potential. The quantum potential is the crucial entity which allows us to understand the features of the quantum world determined by Bohm's pilot wave theory. The mathematical expression of quantum potential (9) shows that this entity does not have the usual properties expected from a classic potential. Equation (9) 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. 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. According to the authors, the fact that the action of quantum potential on a particle is like-space means that the medium of space has clearly an important role in determining the motion of a subatomic particle. On the basis of the formula (9), 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 the three physical coordinates of space. One can say that the formula (9) of quantum potential contains the idea of space as an immediate information medium in an implicit way.

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. In fact, in Bohm's version of quantum mechanics for a many-body system, the equation of motion of the $i-$th in particle, in the limit of big separations, assumes the form

$$m_i \frac{\partial^2 \vec{x}_i}{\partial t^2} = -\left[\nabla_i Q\left(\vec{x}_1, \vec{x}_2, ..., \vec{x}_n\right) + \nabla_i V_i\left(\vec{x}_i\right)\right] \tag{11}$$

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 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" [31].

The appearance of non-separability and non-locality in the Bohm approach led Bell to his famous inequalities [32]. 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. The reader can find more details as regard this topic in the reference [33] of Bohm and Hiley.

Further detailed investigations into these questions in the Bohm approach led to the idea that, inside Bohm's picture, the Cartesian order could no longer be used to explain quantum processes, in particular quantum non-locality. If one takes into account Bohm's results about quantum theory and non-locality, it seems legitimate and also necessary to find and consider a radically new order in which to understand quantum phenomena.

In this regard, already in 1960 Geoffrey Chew [34] 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 intention behind the introduction of the implicate 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. In this way Bohm in his last years departed from de Broglie's pilot wave : he suggested the necessity to consider non-locality as a primary fundamental characteristic of space-time, to introduce an intrinsic non-locality of the quantum world. The idea of the implicate order can be collocated just in this context. Bohm's work was practically directed towards an overcoming of the traditional role of space-time (which instead was present in de Broglie's original view), and to develop a theory of space-time where the quantum concepts appear as structural elements of the world which can be expressed through opportune topological constructions. In Bohm's view the non-locality is a characteristic subtended of space-time and the particles are seen as vibration modes of the global field which is the dynamical expression of the fundamental level, of the deep geometrical structure. Bohm's project was to develop a top-down approach : to introduce a global ontological structure and to try to obtain the form of the objects which emerge from this as manifestations of the undivided totality. As regards his research on the implicate order, conducted mainly with Hiley, Bohm used very refined mathematical instruments, in particular directed his attention towards the non-commutative geometries, the non-linearity and the discreteness.

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 [35].

The considerations of Chew, the research of Bohm and Hiley clearly show the legitimacy to explain non-locality of the quantum phenomena on the basis of approaches different from the space-time manifold. Here the crucial perspective proposed by the authors is thus the following : bohmian implicate order (or analogously Hiley's pre-space) can be assimilated to the idea of physical space as an immediate information medium (and where thus time exists only as a numerical order of events) in the form of the special state of quantum potential. Since quantum potential can explain the origin of non-locality and has a like-space action and since on the basis of the treatment made in this chapter the instantaneous communication between two quantum particles can be seen as an effect of space which functions as a direct information medium, it exists the possibility that there is a sort of correspondence between quantum potential and physical space, in particular that quantum potential can be interpreted as the special "state" of physical space in the presence of microscopic processes, and thus of quantum particles. 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 two particles into consideration [36].

5 A time-symmetric formulation of bohmian quantum mechanics and the symmetrized quantum potential

According to the interpretation proposed in the previous chapter, in EPR-type experiments the instantaneous communication between two 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 information medium between them. Moreover, we have underlined that the instantaneous communication between two particles in EPR-type experiments is characterized by a sort of symmetry : it occurs both if one intervenes on one and if one intervenes on the other, in both cases the same type of process (namely the instantaneous communication between the two particles) 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, namely on the numerical order of the events. However the quantum laws (both in the standard version and in bohmian mechanics) are not time-symmetric and therefore, by inverting the sign of the numerical order of the events, the filming of the process could not correspond to what physically happens. The quantum potential (9), although has a like-space, an instantaneous action, however comes from Schrödinger equation which is not time-symmetric and therefore its expression cannot be considered completely satisfactory from the mathematical point of view just because it can meet problems inverting the sign of time. Thus also the original bohmian approach, although allows us to explain in a clear way quantum non-locality, cannot be considered completely convincing because it is not time-symmetric.

On the basis of these considerations, it turns out to be legitimate to face the question to interpret in the correct way, also in symmetric terms in the exchange of t in $-t$, every quantum process and to take therefore under consideration an extension of Bohmian mechanics that can be symmetrized by inverting the sign of the time. As a consequence, a symmetrized version of quantum potential, able thus to explain a symmetric and instantaneous communication between subatomic particles must be taken into consideration in order to represent a better mathematical 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

$$i\hbar\frac{\partial}{\partial t}\left|\psi(t)\right\rangle = H\left|\psi(t)\right\rangle \tag{12}$$

because the substitution $t \rightarrow -t$ 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 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 take into consideration 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. A solution to the problem of time-symmetry in quantum mechanics (and therefore a way to provide the correct mathematical description of physical space as a direct information medium between elementary particles) already exists : it is 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 [37]. 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 $|C(t)\rangle$ to the time-symmetric equation
$$\begin{pmatrix} H 0 \\ 0\ -H \end{pmatrix} |C(t)\rangle = i\hbar \frac{\partial}{\partial t} |C(t)\rangle \tag{13}$$
where $|C(t)\rangle = \begin{pmatrix} \psi(t) \\ \phi(t) \end{pmatrix}$, $\psi(t)$ 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 $|C_+\rangle = |\psi\rangle + T\,|\phi\rangle$, and as a final boundary condition on $|C_-\rangle = |\psi\rangle - T\,|\phi\rangle$ 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 $|C(t)\rangle$ at times $t_1, t_2, ..., t_n$ is

$$P_0 = \prod_{n=1}^{N-1} \left(C_-(t_n^+)\right) \left(C_+(t_n^+)\right) \left(C_+(t_{n+1}^-)\right) \left(C_-(t_{n+1}^-)\right) \tag{14}$$

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 good 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 experiment.

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 (13). In this regard, just like in the original bohmian theory, we decompose the time-symmetric equation (13) into two real equations, by expressing the wave functions ψ and ϕ in polar form :

$$\psi = R_1 e^{iS_1/\hbar} \tag{15}$$

$$\phi = R_2 e^{iS_2/\hbar} \tag{16}$$

where R_1 and R_2 are real amplitude functions and S_1 and S_2 are real phase functions. Inserting (15) and (16) into (13) 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

$$\frac{\partial}{\partial t}\begin{pmatrix} S_1 \\ S_2 \end{pmatrix} + \frac{1}{2m}\begin{pmatrix} (\nabla S_1)^2 \\ (\nabla S_2)^2 \end{pmatrix} - \frac{\hbar^2}{2m}\begin{pmatrix} \frac{\nabla^2 R_1}{R_1} \\ -\frac{\nabla^2 R_2}{R_2} \end{pmatrix} + \begin{pmatrix} V \\ -V \end{pmatrix} = 0 \tag{17}$$

and the imaginary part may be written in the form

$$\frac{\partial}{\partial t}\begin{pmatrix} R_1^2 \\ R_2^2 \end{pmatrix} + \nabla \cdot \begin{pmatrix} \frac{R_1^2 \nabla S_1}{m} \\ \frac{R_2^2 \nabla S_2}{m} \end{pmatrix} = 0 \tag{18}$$

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

$$Q = -\frac{\hbar^2}{2m}\begin{pmatrix} \frac{\nabla^2 R_1}{R_1} \\ -\frac{\nabla^2 R_2}{R_2} \end{pmatrix} \tag{19}$$

where R_1 is the amplitude function of ψ and R_2 is the amplitude function of ϕ. The equation of motion of the particle (17) can be expressed also in the form

$$m\frac{d^2\vec{x}}{dt^2} = -\nabla \begin{pmatrix} V - \frac{\hbar^2}{2m}\frac{\nabla^2 R_1}{R_1} \\ -V + \frac{\hbar^2}{2m}\frac{\nabla^2 R_2}{R_2} \end{pmatrix} \tag{20}$$

which can be seen as a symmetrized quantum equation of motion. The quantum potential (19) can be considered the starting-point to have a symmetry in time in bohmian quantum mechanics [38].

With the introduction of a wave function at two components $|C(t)\rangle = \begin{pmatrix} \psi(t) \\ \phi(t) \end{pmatrix} = \begin{pmatrix} R_1 e^{iS_1/\hbar} \\ R_2 e^{iS_2/\hbar} \end{pmatrix}$ (which satisfies the time symmetric equation (13)) and the consequent equations (17), (18), (19) and (20), the postulates of de Broglie-Bohm pilot wave theory can be generalized in more fundamental postulates of a symmetrized bohmian mechanics :

– An individual physical system comprises a wave propagating in space and time together with a point particle which moves under the guidance of the wave.
– The wave is mathematically described by $|C(t)\rangle = \begin{pmatrix} \psi(t) \\ \phi(t) \end{pmatrix} = \begin{pmatrix} R_1 e^{iS_1/\hbar} \\ R_2 e^{iS_2/\hbar} \end{pmatrix}$, a solution to the Schrödinger symmetrized equation (13).
– The particle motion is obtained as the solution to the equation (17) or to the equivalent equation (20). To solve these equations (17) and (20) we have to specify the initial condition $\vec{x}_0$. An ensemble of possible motions associated with the same wave $|C(t)\rangle = \begin{pmatrix} \psi(t) \\ \phi(t) \end{pmatrix} =$

$\begin{pmatrix} R_1 e^{iS_1/\hbar} \\ R_2 e^{iS_2/\hbar} \end{pmatrix}$ is generated by varying $\vec{x}_0$.

– The probability that a particle in the ensemble lies between the points $\vec{x}$ and $\vec{x} + d\vec{x}$ at time t is given by $\begin{pmatrix} R_1^2 (\vec{x}, t) \\ R_2^2 (\vec{x}, t) \end{pmatrix} d^3x$. This postulate has the effect of selecting among all the possible motions implied by the laws (17) and (20) those that are compatible with an initial distribution $\begin{pmatrix} R_{10}^2 (\vec{x}, t) \\ R_{20}^2 (\vec{x}, t) \end{pmatrix}$.

Let us examine now in more detail the form of the symmetrized quantum potential (19). As one can easily see, just like the quantum potential of the original Bohm theory, also the symmetrized quantum potential (19) 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 (19) 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 $-t$).

With the introduction of the symmetryzed quantum potential, we can say that, in the presence of quantum particles, space assumes a special "state" at two components that determines the following facts. The first component of this special state $Q_1 = -\frac{\hbar^2}{2m}\frac{\nabla^2 R_1}{R_1}$ regards the forward-time process : it practically coincides with the original Bohm's quantum potential, allows us to explain quantum processes in terms of well-defined motions of particles (as regards the observable effects of Bohm's quantum potential, the reader can find details in the results obtained, for example, by Philippidis, Dewdney, Hiley and Vigier about the classic double-slit experiment, tunnelling, trajectories of two particles in a potential of harmonic oscillator, EPR-type experiments, experiments of neutron-interferometry [39, 40]) and determines a non-local, instantaneous communication on the particle into consideration. Instead the second component $Q_2 = \frac{\hbar^2}{2m}\frac{\nabla^2 R_2}{R_2}$ regards the time-reverse process, reproduces what physically happens if one would imagine to film a quantum process backwards : it allows us to explain quantum phenomena in the most correct and complete way from the point of view of the symmetry in time. Moreover, according to the authors, the opposed sign of the second component with respect to the first component translates from the mathematical point of view the idea that, in a quantum process, time exists only as a measuring system of the numerical order of material changes : the sign of the second component seems to indicate that it is not possible to go backwards in the physical time intended as a numerical order. This peculiar interpretation of quantum non-locality in the context of the symmetryzed quantum potential can also be called as the "immediate symmetric interpretation" of quantum non-locality.

In order to illustrate better the fundamental equations (17) and (19) of the symmetrized extension of bohmian mechanics, let us consider the simple example of the one-dimensional harmonic oscillator, subjected thus to the potential $V = \frac{1}{2}m\omega^2 x^2$. In this particular case equation (17) assumes the form

$$\frac{\partial}{\partial t}\begin{pmatrix} S_1 \\ S_2 \end{pmatrix} + \frac{1}{2m}\begin{pmatrix} (\nabla S_1)^2 \\ (\nabla S_2)^2 \end{pmatrix} - \frac{\hbar^2}{2m}\begin{pmatrix} \frac{\nabla^2 R_1}{R_1} \\ -\frac{\nabla^2 R_2}{R_2} \end{pmatrix} + \begin{pmatrix} \frac{1}{2}m\omega^2 x^2 \\ -\frac{1}{2}m\omega^2 x^2 \end{pmatrix} = 0 \quad (17a),$$

the stationary states are given by $C(t) = \begin{pmatrix} u_n(x)\, e^{-iE_n t/\hbar} \\ u_n(x)\, e^{iE_n t/\hbar} \end{pmatrix}$ (where $u_n(x)$ are real functions proportional to Hermite polynomials and $E_n = \left(n + \frac{1}{2}\right)\hbar\omega$, n=0,1,2,... is the quantum number associated with each stationary state) and the quantum potential which derives from (17a) is

$$Q = \begin{pmatrix} \left(n + \frac{1}{2}\right)\hbar\omega - \frac{1}{2}m\omega^2 x^2 \\ -\left(n + \frac{1}{2}\right)\hbar\omega + \frac{1}{2}m\omega^2 x^2 \end{pmatrix} \quad (19a).$$

The first component of the symmetrized quantum potential (19a) is the real physical component which can explain the forward-time process of the instantaneous action on the particle subjected to the potential $V = \frac{1}{2}m\omega^2 x^2$ while the second component of the symmetrized quantum potential allows us to recover the symmetry in time in quantum processes regarding the harmonic oscillator and thus to interpret in the correct way the behaviour of the harmonic oscillator if one would imagine to film the process backwards.

In analogy to what happens in bohmian original theory, also in this symmetrized extension the quantum potential (19) 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 (19) the total energy of the physical system would not be conserved. In fact, equation (17) can also be written in the equivalent form

$$\frac{1}{2m}\begin{pmatrix}(\nabla S_1)^2\\(\nabla S_2)^2\end{pmatrix}-\frac{\hbar^2}{2m}\begin{pmatrix}\frac{\nabla^2 R_1}{R_1}\\-\frac{\nabla^2 R_2}{R_2}\end{pmatrix}+\begin{pmatrix}V\\-V\end{pmatrix}=-\frac{\partial}{\partial t}\begin{pmatrix}S_1\\S_2\end{pmatrix} \tag{21}$$

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 symmetrized quantum potential (19) energy would not be conserved. Equation (21) 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

$$-\frac{\hbar^2}{2m}\begin{pmatrix}\frac{\nabla^2 R_1}{R_1}\\-\frac{\nabla^2 R_2}{R_2}\end{pmatrix}\to\begin{pmatrix}0\\0\end{pmatrix} \tag{22}$$

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

$$\frac{\partial}{\partial t}\begin{pmatrix}S_1\\S_2\end{pmatrix}+\frac{1}{2m}\begin{pmatrix}(\nabla S_1)^2\\(\nabla S_2)^2\end{pmatrix}+\begin{pmatrix}V\\-V\end{pmatrix}=0 \tag{23}$$

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 symmetrized quantum potential (19) 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 symmetrized quantum potential (19) 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.

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

$$Q = \sum_{i=1}^{N} -\frac{\hbar^2}{2m_i}\begin{pmatrix}\frac{\nabla_i^2 R_1}{R_1} \\ -\frac{\nabla_i^2 R_2}{R_2}\end{pmatrix} \tag{24}$$

The symmetrized quantum potential (24) can explain quantum nonlocality 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. According to the authors' point of view, this formula (24) 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 (24) as the most adequate candidate to present in the correct way the idea of space as a direct information medium between elementary particles. The first component of (24) allows us to interpret the forward-time process of the instantaneous communication between quantum particles with the idea of space as a direct information medium. The second component of (24) allows us to recover a symmetry in time and thus to interpret in the correct way a process of an instantaneous communication with the idea of space as an immediate information medium if one would imagine to film the process backwards. In virtue of its features, it is the symmetrized quantum potential (24) 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. As a consequence, according to the symmetryzed quantum potential approach, in EPR-type experiments space acts as an immediate information medium in the sense that the first component of the symmetryzed quantum potential makes physical space an "immediate information medium" which keeps two elementary particles in an immediate contact (while the second component of the symmetryzed quantum potential allows us to reproduce the symmetry in time of this communication).

6 The idea of space as an immediate information medium in the quantum gravity domain : the symmetrized extension of Wheeler-DeWitt equation and the symmetrized quantum potential for gravity

If at the fundamental level of quantum processes, non local correlations are due to a background space which acts as a direct information medium between the particles under consideration, it is legitimate consider the possibility that also in the quantum gravity domain space functions as a direct information medium. In this regard, in this chapter we want to focus the attention of the reader on a mathematical model of quantum gravity (recently developed by the authors) in which the idea of stage of processes as a direct, immediate information medium can be embedded. The crucial idea that is at the basis of this model is to build a symmetrized version of the bohmian approach of Wheeler-DeWitt equation and thus to introduce the considerations made in chapter 5 inside Wheeler-DeWitt equation.

As we know, in quantum gravity and cosmology universe can be described by a wave-functional Ψ which satisfies the Wheeler-DeWitt (WDW) equation (here we have made the position $\hbar = c = 1$) :

$$\left[(8\pi G)\, G_{abcd} p^{ab} p^{cd} + \frac{1}{16\pi G}\sqrt{g}\left(2\Lambda - {}^{(3)}R\right)\right]\Psi = 0 \qquad (25)$$

where $G_{abcd} = \frac{1}{2}\sqrt{g}\left(g_{ac}g_{bd} + g_{ad}g_{bc} - g_{ab}g_{cd}\right)$ is the supermetric, p^{ab} are the momentum operators related to the 3-metric g_{ab}, $g = \det g_{ij}$, ${}^{(3)}R$ is the 3-dimensional curvature scalar, Λ is the cosmological constant, G is the gravitational constant. In the bohmian approach, by decomposing the wave-functional Ψ in polar form $\Psi = Re^{iS/\hbar}$ the WDW equation becomes

$$(8\pi G)\, G_{abcd}\frac{\delta S}{\delta g_{ab}}\frac{\delta S}{\delta g_{cd}} - \frac{1}{16\pi G}\sqrt{g}\left(2\Lambda - {}^{(3)}R\right) + Q_G = 0 \qquad (26)$$

where

$$Q_G = \hbar^2 N g G_{abcd}\frac{1}{R}\frac{\delta^2 R}{\delta g_{ab}\delta g_{cd}} \qquad (27)$$

N being the lapse function. The term Q_G can be defined "quantum potential for gravity". Moreover, in the bohmian approach, Einstein's equations – in absence of source of matter-energy - assume the following forms :

$$R^{\mu\nu} - \frac{1}{2}g^{\mu\nu}R = -\frac{1}{N}\frac{\delta\int Q_G d^3x}{\delta g_{ij}} \tag{28}$$

for the dynamical parts, and

$$R^{0\nu} - \frac{1}{2}g^{0\nu}R = \frac{Q_G}{2\sqrt{-g}}g^{0\nu} \tag{29}$$

for the non-dynamical part. (The reader can find some interesting developments as regards the bohmian approach to WDW equation, for example, in the references [41, 42, 43, 44, 45, 46]).

Equations (26), (28) and (29) show that the term Q_G is responsible of the behaviour of the universe intended as a whole. On the basis of equations (26), (27), (28) and (29) regarding the bohmian approach to WDW equation, one can say that universe presents a sort of aggregate, comprehensive "order" which guides it : this order is just determined by the "quantum potential for gravity" (27). The quantum potential for gravity (27) can be thus considered as a sort of generalization of the bohmian quantum potential to the universe as a whole. Just like in Bohm's pilot wave theory the quantum potential (9) guides the motion of a subatomic particle in the regions where the wave function of that particle is more intense, in analogous way the quantum potential for gravity (27) can be considered the crucial element that guides the behaviour of the universe.

Moreover, just like for the quantum potential (9) of the original Bohm's pilot wave theory, also for the quantum potential for gravity (27) we can make important considerations which derive from its mathematical expression. In fact, if the quantum potential for subatomic particles (9) has a like-space, instantaneous action, in analogous way also the quantum potential of gravity (27) has an instantaneous, like-space action. As a consequence, if the original Bohm's quantum potential (9) can be associated – in the context of quantum non-locality in the subatomic world - with the idea of space as an immediate information medium between subatomic particles, in analogous way the quantum potential for gravity (27) - just in virtue of its non-local instantaneous action – can be associated with the idea of space in the quantum gravity domain as an immediate information medium. The quantum potential for gravity (27) can be thus considered an appropriate candidate to represent the special state of space in the quantum gravity domain as an immediate, direct information medium.

However, just like it happens in the original Bohm's pilot wave theory, also the original Bohm's approach to quantum gravity cannot be considered completely convincing from the point of view of the mathematical symmetry in time. The standard quantum laws regarding WDW equation (and thus also the Bohm's approach to WDW equation which derives from it) are not time-symmetric and therefore if one inverts the sign of time, the filming of a process in the quantum gravity domain could not correspond to what physically happens. In particular, in the Bohm's approach, the quantum potential for gravity (27) - although has a like-space, an instantaneous action - just because it comes from WDW equation which is not time-symmetric, cannot be considered completely satisfactory from the mathematical point of view, in the sense that it can meet problems by inverting the sign of time.

On the basis of these considerations, in order to have a more appropriate candidate for the state of space in the quantum gravity domain (and thus for the universe as a whole), which could assure a mathematical symmetry in the exchange of t in $-t$, it is necessary to consider a symmetrized version of the quantum potential for gravity. In this regard, before all, the problem of time-symmetry in the standard interpretation of WDW equation can be resolved in analogous manner to the considerations made by Wharton in his attempt to develop a time-symmetric formulation of standard quantum mechanics, by considering a time-symmetric extension of WDW equation of the form

$$\begin{pmatrix} H & 0 \\ 0 & -H \end{pmatrix} C = 0 \tag{30}$$

where

$$H = \left[(8\pi G)\, G_{abcd} p^{ab} p^{cd} + \frac{1}{16\pi G} \sqrt{g} \left(2\Lambda - {}^{(3)}R \right) \right] \tag{31}$$

and $C = \begin{pmatrix} \Psi \\ \Phi \end{pmatrix}$, Ψ is the solution of the standard WDW equation, Φ is the solution of the time-reversed WDW equation.

The second step is to build a time-symmetric reformulation of the bohmian approach to WDW equation in the light of the symmetrized WDW equation (29). This can be obtained in analogous way to the program followed in chapter 5 regarding time-symmetric extension of Bohm's pilot wave theory. The crucial point is to decompose the time-symmetric WDW equation (30) into two real equations, by expressing the wave-functionals Ψ and Φ in polar form :

$$\Psi = R_1 e^{iS_1} \tag{32}$$

$$\Phi = R_2 e^{iS_2} \tag{33}$$

where R_1 and R_2 are real amplitude functionals and S_1 and S_2 are real phase functionals. Inserting (32) and (33) into (30) and separating into real and imaginary parts we obtain the following quantum Hamilton-Jacobi equation for quantum general relativity

$$(8\pi G)\, G_{abcd} \begin{pmatrix} \frac{\delta S_1}{\delta g_{ab}} \frac{\delta S_1}{\delta g_{cd}} \\ \frac{\delta S_2}{\delta g_{ab}} \frac{\delta S_2}{\delta g_{cd}} \end{pmatrix} - \frac{1}{16\pi G}\sqrt{g} \begin{pmatrix} 2\Lambda - {}^{(3)}R \\ -2\Lambda + {}^{(3)}R \end{pmatrix} \left(2\Lambda - {}^{(3)}R\right) + \begin{pmatrix} Q_{G1} \\ Q_{G2} \end{pmatrix} = 0 \tag{34}$$

where

$$Q_{G1} = \hbar^2 N g G_{abcd} \frac{1}{R_1} \frac{\delta^2 R_1}{\delta g_{ab} \delta g_{cd}} \tag{35}$$

$$Q_{G2} = -\hbar^2 N g G_{abcd} \frac{1}{R_2} \frac{\delta^2 R_2}{\delta g_{ab} \delta g_{cd}} \tag{36}$$

In this way a symmetrized extension of bohmian version of WDW equation emerges. This approach is characterized by a symmetrized quantum potential for gravity at two components

$$Q_G = \begin{pmatrix} \hbar^2 N g G_{abcd} \frac{1}{R_1} \frac{\delta^2 R_1}{\delta g_{ab} \delta g_{cd}} \\ -\hbar^2 N g G_{abcd} \frac{1}{R_2} \frac{\delta^2 R_2}{\delta g_{ab} \delta g_{cd}} \end{pmatrix} \tag{37}$$

The first component (35) coincides with the original "quantum potential for gravity" (27) : it can explain the forward-time process of the space-like, instantaneous action of quantum gravity. The second component (36) must be introduced in order to reproduce also the time-reverse of a process in the quantum gravity domain through the instantaneous action (this second component assures that one could see what really happens if one would imagine to film the process by going backwards in time). As a consequence, just because it allows us to recover a symmetry in time, the symmetrized quantum potential for gravity can be considered a good mathematical candidate for the state of space in the quantum gravity domain that expresses a direct, immediate information medium (just like the symmetrized quantum potential (24) can be considered the starting point to develop mathematically the idea of space as an immediate information medium between elementary particles). The symmetrized quantum potential for gravity implies that also in the quantum gravity domain a fundamental stage of physical processes exists which acts as an immediate information medium [47].

On the basis of the argumentations provided in chapters 5 and 6 as regards a symmetrized Bohm's version of non-relativistic quantum mechanics and a symmetrized Bohm's version of WDW equation, we can therefore conclude that both the wave functions of subatomic particles and the wave-functionals of the gravitational field in the quantum gravity domain determine a space medium, a special state of physical reality (represented, respectively, by the symmetrized quantum potential and the symmetrized quantum potential for gravity) which acts as a direct, immediate information medium in its respective domain.

7 Conclusions

On the basis of the treatment made in this article, time that is measured with clocks is not an independent dimension that flows on its own but is a numerical order of the material change i.e. motion that runs in a timeless space. This understanding introduces interesting perspectives in the interpretation of the instantaneous communication between subatomic particles in an EPR-type experiment. Information transfer between subatomic particles is instantaneous because space functions as a direct, as an immediate information medium. The symmetrized quantum potential appears as the most adequate candidate to represent mathematically the idea of space as a direct information medium. In the quantum domain, space assumes the special state represented by the symmetrized quantum potential which produces an instantaneous communication between the particles under consideration and allows us to interpret in the correct way both the forward-time and the time-reverse of the same physical process. Forward-time and time-reverse of a physical process are a matter of numerical order of material changes in a timeless space. Moreover, as regards the idea of a background timeless space as an immediate medium of information, the symmetrized quantum potential seems to occupy a fundamental role also in the quantum gravity domain. In a complete physical theory the possibility is opened that a fundamental arena in which space functions as an immediate information medium and which is associated with a symmetrized quantum potential should assume a crucial role and all the objects of physics might emerge from it as special states.

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