Nonlocality and the symmetrized quantum potential

Davide Fiscaletti[1,a)] and Amrit Srečko Šorli[2,b)]
[1]*SpaceLife Institute, San Lorenzo in Campo, Italy*
[2]*Scientific Research Centre BISTRA, Ptuj, Slovenija*

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Abstract: Quantum nonlocality can be difficultly understood and explained starting from the idea that the spacetime manifold characteristic of special relativity is a fundamental entity: it is due to a quantum potential which is equivalent to a spacelike, instantaneous action between the particles in consideration. In virtue of the features of quantum potential, a new order must be introduced to understand quantum phenomena, in particular quantum nonlocality. 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) of a symmetry in time in quantum mechanics is needed, a symmetrized reformulation of bohmian mechanics is introduced and analyzed. © *2008 Physics Essays Publication*. [DOI: 10.4006/1.3033291]

Résumé: 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: Nonlocality; Physical Space; Quantum Potential; Time Symmetry; Symmetrized Quantum Potential.

I. 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 nonlocality and entanglement, by the nonseparability of subatomic particles.

To be explicit and illustrate quantum nonlocality, 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 $\frac{1}{2}$ atoms in a singlet state,

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

where $f_1(\vec{x}_1)$, $f_2(\vec{x}_2)$ are nonoverlapping 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, $\hat{s}_{z_1} u_\pm = \pm(\hbar/2)u_\pm$, $\hat{s}_{z_2} v_\pm = \pm(\hbar/2)v_\pm$. 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 Eq. (1) reduces to the first of its summands,

$$\psi \to f_1 f_2 u_+ v_-. \tag{2}$$

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

a)fiscalettidavide@libero.it
b)sorli.bistra@gmail.com

nonlocality and nonseparability in Euclidean three-dimensional space: this comes about because the spin measurements couple the spin and space variables.

II. QUANTUM NONLOCALITY AND BOHMIAN QUANTUM POTENTIAL

Quantum nonlocality can be easily explained in the context of Bohm's version of quantum mechanics. In de Broglie–Bohm's pilot wave theory the nonlocal 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:

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

(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

$$Q=-\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}, \tag{4}$$

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

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

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 Eq. (4) tells us clearly that the quantum potential depends on how the amplitude of the wave function varies in space. The presence of the Laplace operator indicates that the action of this potential is like space, namely creates onto the particle a nonlocal, 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 behavior 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 instantaneous information about the overall experimental arrangement. Moreover, this information can be regarded as being active in the sense that it modifies the behavior 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 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 space is the medium responsible of the behavior of quantum particles. Considering the double-slit experiment, the information that quantum potential transmits to the particle is instantaneous just because it is spatial information, is linked to physical space.

It is also important to underline that in the standard interpretation of quantum mechanics the nonlocality 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 nonlocality. 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 ith 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 ith particle in the limit of big separations assumes the form

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

and thus depends on the coordinates of all the n particles of the system: this determines just nonlocal 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 nonseparability and nonlocality in the Bohm approach led Bell to his famous inequalities.[8] Of course nonlocality 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 nonlocality. 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 nonlocal correlations.

In 1980 Bohm suggested that the new order in which to understand quantum phenomena would be based on process and this new order called 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 behavior 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 prespace, 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 nonlocality.[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 spacelike points.[12] These points are active in the sense that each point is a process that preserves its identity and its incidence relations with neighboring 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 symplectic 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 noncommuting algebra. This process allows partial views because nature is basically participatory.

The considerations of Chew and the research of Bohm and Hiley clearly show the legitimacy to understand and explain quantum nonlocality 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 it 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 prespace 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 clearly has an important role in determining the motion of a subatomic particle. On the basis of the formula Eq. (4), one can say that space is the medium responsible for the behavior of quantum particles. One can say that the quantum potential Eq. (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 being 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 Sec. I), 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 a 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 behavior of particle B and the opposite.[15]

In synthesis, one can say that in EPR experiments quantum potential makes physical space an "immediate information medium" between elementary particles. In EPR experiments the behavior 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.

III. A TIME-SYMMETRIC FORMULATION OF BOHMIAN QUANTUM MECHANICS

According to the interpretation proposed in the previous section, the instantaneous, nonlocal communication between two quantum particles can be seen as a consequence of the fact that the information between the two particles has no 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 filming 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 depends 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 Eq. (4) has a like space, an instantaneous action, it however comes from the 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 it allows us to explain quantum nonlocality, 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 section we propose to introduce a new symmetrized version of the 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,

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

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 nonlocality. 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 section 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 of 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 $|C(t)\rangle$ to the time-symmetric equation,

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

where $|C(t)\rangle=\binom{\psi(t)}{\phi(t)}$, $\psi(t)$ is the solution of the standard Schrödinger equation; $\psi(t)$ 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 $t_1, t_2, \ldots, t_n$ is

$$P_0 = \prod_{n=1}^{N-1} (C_-(t_n^+))(C_+(t_n^+))(C_+(t_{n+1}^-\ )(C_-(t_{n+1}^-)), \tag{9}$$

where $N>1$ and each measurement is constrained by the boundary conditions

$$Q_M|C_\pm(t_0^\pm\ \rangle = q_n|C_\pm(t_0^\pm\ \rangle.$$

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 nonlocality is due to a 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 Eq. (8). In this regard, just like in the original Bohmian theory, we decompose the time-symmetric equation Eq. (8) into two real equations, by expressing the wave functions ψ and ϕ in polar form,

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

$$\phi = R_2 e^{iS_2/\hbar}, \tag{11}$$

where R_1 and R_2 are real amplitude functions and S_1 and S_2 are real phase functions. Inserting Eqs. (10) and (11) into Eq. (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

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

and the imaginary part may be written in the form

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

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

$$Q = -\frac{\hbar^2}{2m}\begin{pmatrix} \dfrac{\nabla^2 R_1}{R_1} \\ -\dfrac{\nabla^2 R_2}{R_2} \end{pmatrix}, \tag{14}$$

where R_1 is the amplitude function of ψ and R_2 is the amplitude function of ϕ. The symmetrized quantum potential Eq. (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 Eq. (14) has an action which is stronger when the mass is more comparable with the Planck constant, and the Laplace operator indicates that the action of this potential is like space, nonlocal, instantaneous. The difference from the original bohmian mechanics lies in the fact that Eq. (14) has two components, namely depends also on the wave function concerning the time-reverse process, and therefore its spacelike, nonlocal, 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 analyze the mathematical expression of the symmetrized quantum potential Eq. (14), we can make the following important considerations. The first component, $Q_1 = -(\hbar^2/2m_i)(\nabla_i^2 R_1/R_1)$, indicates that in the forward-time process the action of the quantum potential on the particle under consideration is instantaneous, spacelike; the second component, $Q_2 = (\hbar^2/2m)(\nabla^2 R_2/R_2)$, 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 Eq. (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 Eq. (14) the total energy of the physical system would not be conserved. In fact, Eq. (12) can also be written in the equivalent form,

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

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

$$Q=-\frac{\hbar^2}{2m}\begin{pmatrix}\dfrac{\nabla^2 R_1}{R_1}\\-\dfrac{\nabla^2 R_2}{R_2}\end{pmatrix}, \tag{14$'$}$$

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

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

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

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

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 Eq. (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 on 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 the double-slit experiment are explained by saying that the quantum potential Eq. (14) contains 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

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

The symmetrized quantum potential Eq. (18) 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. More precisely, the first component, $Q_1=\Sigma_{i=1}^{N}-(\hbar^2/2m_i)(\nabla_i^2 R_1/R_1)$, explains the instantaneous communication between subatomic particles in many-body systems in the forward time; the second component, $Q_2=\Sigma_{i=1}^{N}(\hbar^2/2m_i)(\nabla_i^2 R_2/R_2)$, allows us to reproduce in the correct way the time reverse of this instantaneous communication. According to the authors' point of view, this formula Eq. (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 Eq. (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 Eq. (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.

IV. 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 nonlocality. A new order is necessary which must take into account that nonlocality 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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