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*Three-dimensional space as a medium of quantum entanglement*

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Trójwymiarowa przestrzeń jako ośrodek splątania kwantowego

**ABSTRACT**

Most physicists today still conceptualize time as a part of the physical space in which material objects move, although time has never been observed and measured as a part of the space. The concept of time here presented is that time measured with clocks is merely the numerical order of material change, i.e. motion in a three-dimensional space. In special relativity the Minkowskian four-dimensional space-time can be replaced with a three-dimensional space where time does not represent a fourth coordinate of space but must be considered merely as a mathematical quantity measuring the numerical order of material changes. By quantum entanglement the three-dimensional space is a medium of a direct information transfer between quantum particles. Numerical order of non-local correlations between subatomic particles in EPR-type experiments and other immediate quantum processes is zero in the sense that the three-dimensional space acts as an immediate information medium between them.

**Key words:** space, time, numerical order of material change, run of clocks, photon motion, quantum entanglement, quantum entropy, symmetrized quantum potential

**1. INTRODUCTION**

In Newtonian physics, as well as in standard quantum mechanics, time is postulated as a special physical quantity and plays the role of the independent variable of physical evolution. Newton or Hamilton equations, as well as the Schrödinger equation, are introduced on the basis of the underlying assumption

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that an idealized, absolute time  $t$  in which the dynamics is defined, exists. However, it is an elementary observation that we never really measure this idealized time  $t$ , that this idealized, absolute time does not ever appear in laboratory measurements: we rather measure the frequency, speed and numerical order of material changes. What experimentally exists is only the motion of a system and the tick of a clock. What we realize in every experiment is comparing the motion of the physical system under consideration with the motion of a peculiar clock described by a peculiar tick  $T$ . This means that the duration of material motions has not a primary physical existence, that time as humans perceive it does not exist as an absolute quantity, that time does not flow on its own as an independent variable and thus does not exist as a primary physical reality.

Changes of the state of the universe and, at the same time, changes of the state of any physical system can be considered the primary phenomena which generate evolution of the universe. This evolution can be described by introducing a mathematical parameter, which provides only the ordering of events. In the article *Projection evolution and delayed choice experiment*, A. Gózdź and K. Stefańska have shown that an evolution parameter, “numerical order”, which provides only the order of events, can be easily introduced [1]. In the reference [2], the authors of this article have gone beyond by suggesting the following concept of time: according to this view, the symbol of time  $t$  in all mathematical formalisms of physics is a number which represents the numerical order of material change, i.e. motion and therefore, only the numerical order of the motion of the system under consideration, which is obtained by the clock under consideration, exists.

In the Minkowskian arena of the Special Theory of Relativity the fourth coordinate  $X_4$  of space is spatial, too.  $X_4$  is a product of imaginary number  $i$ , light speed  $c$ , and the numerical order  $t$  of a physical event:  $X_4 = i \cdot c \cdot t$ . On the basis of the mathematical expression of the fourth coordinate, the Minkowski arena is a four-dimensional (4D) space [3]. In the recent article *Special theory of relativity in a three-dimensional Euclidean space* [4] the authors have shown that Minkowski 4D space can be replaced with a three-dimensional Euclidean space with Galilean transformations

$$\begin{aligned} X' &= X - v \cdot t \\ Y' &= Y \\ Z' &= Z \end{aligned} \quad (1)$$

for the three spatial dimensions and Selleri's transformation

$$t' = \sqrt{1 - \frac{v^2}{c^2}} \cdot t \quad (2)$$

for the rate of clocks. The Galilean transformations are valid for both the observers  $O$  and  $O'$  in inertial systems  $o$  and  $o'$ . The transformation of the speed of clocks given by Selleri's formalism [5, 6, 7] 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  $o'$ . In the formalisms (1) and (2), time and space are two separated entities. Equations (1) and (2) determine an arena of Special Relativity in which the temporal coordinate must be clearly considered as a different entity with respect to the spatial coordinates just because the transformation of the speed of clocks between the two inertial systems does not depend on the spatial coordinates. Selleri's results seem thus to suggest that the three spatial coordinates of the two inertial systems turn out to have a primary ontological status, define an arena that must be considered more fundamental than the standard space-time coordinates interpreted in the sense of Einstein. On the basis of equations (1) and (2) one can assume that the real arena of Special Relativity is not a mixed 3D+T space-time but rather a three-dimensional (3D) space and that time does not represent a fourth coordinate of space but exists merely as a mathematical quantity measuring the numerical order of material changes.

The main idea which is at the basis of this article is that evolution in the universe occurs in a 3D space. The article is structured in the following manner. In chapter 2 we will illustrate in what sense a timeless 3D space (where time exists only as a numerical order of events) is the fundamental arena of physical processes (and we will indicate some current research which point in this direction). In chapter 3 we will mention some predictions of our model in the relativistic domain and propose a way in which our theory of space and time could be falsified. Finally, in chapter 4 we will show that, as regards non-local correlations between subatomic particles, the 3D space acts as a direct medium of quantum information transfer (in the picture of Bohm's quantum potential and then of a symmetrized quantum potential).

## 2. THREE-DIMENSIONAL SPACE AS A FUNDAMENTAL ARENA OF PHYSICS

In his paper *Time and Classical and Quantum Mechanics: Indeterminacy versus Discontinuity* Lynds argues that between time and space there is always a difference: "The fact that imaginary numbers when computing space-time intervals and path integrals do not facilitate that when multiplied by  $i$ , that time intervals become basically identical to dimensions of space. Imaginary numbers show up in space-time intervals when space and time separations are combined at near the speed of light, and spatial separations are small, comparing to time intervals. What this illustrates is that although space and time are interwoven in Minkowski space-time, and time is the fourth dimension, time is not spatial dimension: time is always time, and space is always space, as those  $i$ 's keep showing us. There is

always a difference. If there is any degree of space, regardless of how microscopic, there would appear to be inherent continuity i.e. interval in time” [8].

Although Lynds’ conclusion that time is time and space is always space may appear a little questionable (the imaginary space-time interval, in fact, means only an impossibility to connect the points under consideration by a signal equal or slower than the speed of light), according to the authors there is nothing wrong in assuming that time and space are different in their nature, that time is a different entity from space, that time is not a spatial dimension. The crucial starting hypothesis of the view suggested in this paper is that time and space are different in their nature and that the difference between space and time is the following: the fundamental arena of the universe is a 3D space and time is a numerical order of material changes that take place in space.

On the other hand, many researchers are challenged with the view that time is not a fundamental arena of the universe. For example, in their paper *The Mathematical Role of Time and Space-Time in Classical Physics*, Newton C. A. da Costa and Adonai S. Sant’Anna show that time as a fundamental physical arena in which material changes take place can be eliminated: “We use Padoa’s principle of independence of primitive symbols in axiomatic systems in order to discuss the mathematical role of time and space-time in some classical physical theories. We show that time is eliminable in Newtonian mechanics and that space-time is also dispensable in Hamiltonian mechanics, Maxwell’s electromagnetic theory, the Dirac electron, classical gauge fields, and general relativity” [9].

According to several current studies, the mathematical model of space-time does not correspond indeed to a physical reality and a “state space” or a “time-less space” can be proposed as the fundamental arena. In particular, Girelli, Liberati and Sindoni have 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. In this sense this toy-model provides an example where time is not fundamental, but simply an emerging feature [10]. 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  $\Psi_i(x_\mu)$ ,  $i=1, 2, 3$ . Their emerging Lagrangian  $L$  is invariant under the Euclidean Poincarè group  $ISO(4)$  and has thus the general shape

$$L = F(X_1, X_2, X_3) = f(X_1) + f(X_2) + f(X_3); \quad X_i = \delta^{\mu\nu} \partial_\mu \Psi_i \partial_\nu \Psi_i. \quad (3)$$

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

$$\partial_\mu \left( \frac{\partial F}{\partial X_i} \partial^\mu \Psi_i \right) = 0 = \sum_j \left( \frac{\partial^2 F}{\partial X_i \partial X_j} (\partial^\mu X_j) \partial^\mu \Psi_i + \frac{\partial F}{\partial X_i} \partial_\mu \partial^\mu \Psi_i \right). \quad (4)$$

The fields  $\Psi_i(x_\mu)$  can be expressed as  $\Psi_i = \psi_i + \varphi_i$  where  $\varphi_i$  are perturbations which encode both the gravitational and matter degrees of freedom and the functions  $\psi_i$  are classical solutions (of the above Eq. (4)). The Lagrangian for the perturbations  $\varphi_i$  is given by

$$F(\bar{X}_1, \bar{X}_2, \bar{X}_3) + \sum_j \frac{\partial F}{\partial X_j} (\bar{X}) \delta X_j + \frac{1}{2} \sum_{jk} \frac{\partial^2 F}{\partial X_j \partial X_k} (\bar{X}) \delta X_j \delta X_k + \frac{1}{6} \sum_{jkl} \frac{\partial^3 F}{\partial X_j \partial X_k \partial X_l} (\bar{X}) \delta X_j \delta X_k \delta X_l \quad (5)$$

where  $\bar{X}_i = \delta^{\mu\nu} \partial_\mu \psi_i \partial_\nu \psi_i$  and  $\delta X_i = 2 \delta_\mu \psi_i \partial^\mu \psi_i \partial_\mu \varphi_i \partial^\mu \varphi_i$ .

Different choices of the solutions  $\psi_i$  lead to different metrics

$$g_k^{\mu\nu} = \frac{df}{dX_k} (\bar{X}_k) \delta^{\mu\nu} + \frac{1}{2} \frac{d^2 f}{(dX_k)^2} (X_k) \partial^\mu \psi_k \partial^\nu \psi_k \quad (6).$$

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 that, at a fundamental level, time cannot be considered a physical arena, a primary physical reality and that in order to describe physically the evolution clocks provide only a parameter which orders events.

But in what sense clocks provide only the numerical order of a physical event, how can a clock act in a space that, at a fundamental level, is timeless? In this regard, in the recent article *The nature of time: from a timeless Hamiltonian framework to clock time metrology*, Prati has underlined 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. Prati has shown that in a timeless Hamiltonian 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 [11]. The cyclic subsystem acts as a clock reference used for the operative definition of time. An important result of Prati's research is that, as a consequence of the gauge invariance (which transforms one parametric time into another in a way that they are all equivalent) the complex system S can be separated in many ways in a part which constitutes the clock and the rest. But,

now, what does it mean, in physical terms, that a complex physical system can be separated in many ways in a subsystem whose dynamics is described and another subsystem which behaves as a clock? This means clearly that the time provided by each subsystem which acts as a clock cannot be considered as an absolute quantity, and therefore that time as an idealized quantity that flows on its own does not exist: only the ticking of each subsystem acting as a clock exists as physical reality. This implies, in other words, that each subsystem which acts as a clock provides only a description of the dynamics of the other subsystem and that this description is tightly linked to ticking of the clock-subsystem. In synthesis, one can say that each clock-subsystem provides only a measuring reference system for the dynamics of the other subsystem and that this reference system is not absolute; one can say that each subsystem that acts as a clock provides only the numerical order of the dynamics of the other subsystem.

Moreover, recently Pavsic developed a Kaluza-Klein-type model in which the ordinary spacetime of general relativity is replaced with a configuration space  $C$ , a multidimensional manifold equipped with metric, connection and curvature [12]. Inside this model Pavsic showed that the ordinary general relativistic theory for a many particle system is only a special case that derives from a more general action in the configuration space  $C$  for a particular block diagonal metric. The most general action has the form

$$I[X^M] = M \int d\tau [\dot{X}^M \dot{X}^N G_{MN}(X^M)]^{1/2} \quad (7)$$

where  $X^M \equiv X_i^\mu$  (with  $\mu = 0, 1, 2, 3$  and  $i=1, 2, \dots, N$ ,  $N$  being the number of the particles in the configuration) are the coordinates of the point particles of the system,  $M$  has the role of mass in  $C$ ,  $\tau$  is an arbitrary monotonically increasing parameter and  $G_{MN}$  is the metric. The action is proportional to the length of a worldline in  $C$ . The ordinary general relativistic theory for a many particle system derives from the action (7) in the special case

$$G_{MN} = \begin{pmatrix} g_{\mu\nu}(x_1) & 0 & 0 & \dots \\ 0 & g_{\mu\nu}(x_2) & 0 & \dots \\ 0 & 0 & g_{\mu\nu}(x_3) & \dots \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{pmatrix} \quad (8).$$

Inside Pavsic's model, the metric in the configurations space  $C$  is not fixed but is dynamical, so that the total action contains a kinetic term for  $G_{MN}$ :

$$I[X^M, G_{MN}] = I_m + I_g \quad (9)$$

where

$$I[X^M] = \int d\tau M [\dot{X}^M \dot{X}^N G_{MN}(X^M)]^{1/2} = \int d\tau M [\dot{X}^M \dot{X}^N G_{MN}(X^M)]^{1/2} \delta^D(x - X(\tau)) d^D x \quad (10)$$

and

$$I_g = \frac{1}{16\pi G_D} \int d^D x \sqrt{|G|} R \quad (11)$$

where  $R$  is the curvature scalar in  $C$ .

In Pavsic's model, the fact that, on the basis of equations (7), (9), (10) and (11), the action of a system of  $N$  particles in the general relativistic domain does not depend explicitly on an idealized time but only on an arbitrary monotonically increasing parameter  $\tau$ , according to the authors, means that in general relativity time does not exist as a primary physical reality but is only a mathematical device and that the parameter  $\tau$  represents just a measuring device of the mathematical numerical order of material changes, characterizing the system of  $N$  particles under consideration.

In synthesis (also taking into account some current research) according to the authors of this paper, it is legitimate to assume that the fundamental arena in which material changes take place is a 3D space and that time is a different entity from space, is not a primary physical reality that flows on its own: it exists only as a numerical order of material changes measured with clocks. In the universe, material changes are running in space only while time, being merely a mathematical measuring system, is a static concept: it indicates exclusively a numerical order of material changes. Past instants  $t_{-n} \dots t_{-2}, t_{-1}$ , present moment  $t_0$  and future instants  $t_1, t_2 \dots t_n$  exist only as a numerical order of material change in a 3D space. One can move in space only and not in time. Hypothetical travels in time are not possible.

### 3. ABOUT THE PREDICTIONS AND THE FALSIFIABILITY OF THE HERE PRESENTED THEORY OF SPACE AND TIME

As regards the predictions of the model of space and time proposed by the authors, it is important to mention that, in virtue of equations (1) and (2), there is no "time dilation" and there is no "length contraction" in the direction of motion of an inertial system (as it is known in the Special Theory of Relativity). In fact,

on the one hand, it is not true that dilation of time as a 4<sup>th</sup> coordinate of space causes clocks to have a slower rate: what really exists in different inertial systems is the relative velocity of material change (including the run of clocks). On the other hand, as regards “length contraction” some other research leads to the same conclusions of our model. Since 1905, when the Special Theory of Relativity was published, there has been no experimental data on “length contraction” [13].

As regards the possibility to falsify our model, let us consider the falsifiability of the following two statements, A and B:

A. for all experiments, time  $t$  has the same ontological nature of the 3D space and therefore is a fundamental physical entity in which a given experiment occurs;

B. for all experiments, time  $t$ , when measured with clocks, is merely a numerical order of material change taking place in a 3D space, which is a fundamental physical entity in which a given experiment occurs.

Statement A has no basis in the elementary visual perception. This is its weak point. Statement A is falsifiable by an experiment in which time  $t$  does not exist. Such an experiment is, for example, the Coulomb experiment with a torsion balance to measure electrostatic interaction between two metal-coated balls endowed with charges  $q_1$  and  $q_2$  respectively. The Coulomb experiment implies the following mathematical formalism as regards the electrostatic force between the two metal-coated balls:

$$F = K_e \frac{q_1 q_2}{r^2} \quad (12)$$

where  $r$  is their distance.

In this experiment, time is not present as the fundamental entity in which the experiment takes place. To consider statement A as correct, it should be proven that the Coulomb experiment does not take place in space only but also in time, and that time does not affect the electrostatic interaction between the two metal-coated balls. Without this proof this experiment indicates statement A is wrong: formalism (12) indicates experiment takes place only in the 3D space as a fundamental physical entity, not in time.

In the analogous way, in Newton’s measuring of gravitational force between two material objects, time  $t$  as the fundamental physical entity does not exist. Measurement of the gravitational force implies the following mathematical formalism of gravitational force between two material objects of masses  $m_1$  and  $m_2$  situated at distance  $r$ :

$$F = G \frac{m_1 m_2}{r^2} \quad (13).$$

In this experiment, time is not present as the fundamental physical entity in which the experiment takes place. To consider statement A as correct it should be proven that this experiment takes place in time and that time does not affect gravitational force between the two material objects. Without this proof the experiment indicates that statement A is wrong: formalism (13) indicates the experiment takes place only in the 3D space as a fundamental entity, not in time.

Statement B has its basis in the elementary visual perception. This is its strong point. Ocular experience confirms that clocks measure the numerical order of material changes in 3D space as a fundamental entity in which an experiment occurs. Statement B is falsifiable by an experiment where time  $t$  measured with clocks is not the numerical order of material changes. Such an experiment would prove statement B to be wrong; such an experiment is not known yet. An experiment where there is no time is not disproving statement B.

#### 4. BY QUANTUM ENTANGLEMENT 3D SPACE IS A DIRECT MEDIUM OF QUANTUM INFORMATION TRANSFER

According to the concept of space-time, all physical phenomena happen in space and time. This concept cannot explain those physical phenomena where information transfer is immediate. For these phenomena the elapsed clock run is zero. We can appropriately call these phenomena as “immediate physical phenomena”. If phenomena would happen in time as some physical reality, time could never be zero. The core of this article is to present a new concept of space-time as a timeless 3D physical reality where measurable time obtained with clocks is only a numerical order of physical phenomena. Immediate physical phenomena have no numerical order. Immediate physical phenomena are immediate information transfers carried directly by the 3D space which originates from a 3D vacuum. 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 [14–17].

On the other hand, it is important to mention that also quantum electrodynamics predicts the existence of immediate physical phenomena. The QED allows for 0-time phenomena for virtual photons which do not obey normal conservation laws and other rules. These virtual processes of exchange of space-like virtual photons are not related to transfer of any real physical quantity but are characterized by interchange forces which act instantaneously thanks to the medium of space. The fundamental quantum process underlying applications as disparate as the gyromagnetic ratio of the electron and electrical machinery is the so-called

Møller scattering  $ee \rightarrow ee$ . In J. H. Field's paper *Quantum electrodynamics and experiment demonstrate the nonretarded nature of electrodynamical force fields*, a detailed analysis of the quantum amplitude for the Møller scattering shows that the corresponding interchange force 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 [18].

According to the view suggested by the authors of this article, immediate physical phenomena are characterized by a zero numerical order independently on the motion of the observer. Therefore, in this approach the interesting perspective is opened that the zero numerical order regarding the immediate information transfer turns out to have an ontological status similar to the maximum of the light speed of the special theory of relativity.

As we know, in quantum mechanics the world is described by a wave function. The wave function of an isolated microsystem evolves freely according to the Schrodinger evolution, that is certainly one of the most important equations of physics, as it allows us to understand the behaviour of many materials and physical systems, like for example semiconductors and lasers. Quantum mechanics was however originally formulated as a theory of quantum microsystems that interact with classical macrosystems. In the original formulation of the theory, the interaction of a quantum microsystem  $S$  with a classical macrosystem  $O$  is described in terms of "quantum measurements" [19, 20]. After the microsystem  $S$  under consideration interacts with its surroundings, the microsystem and its surroundings then become entangled and they are in a quantum mechanical superposition. If the macrosystem  $O$  interacts with the variable  $q$  of the microsystem  $S$ , and  $S$  is in a superposition of states of different values of  $q$ , then the macrosystem  $O$  measures only one of the values of  $q$ , and the interaction modifies the state of  $S$  by projecting it into a state with that value: in every measurement the wave function of a microsystem collapses into the state specified by the outcome of the measurement. But, is the collapse of the wave function instantaneous? Do properties of subatomic systems become manifest suddenly? When precisely can we say that a given event has happened?

In this regard, in his book *The Landscape of Theoretical Physics: A Global View*, Pavsic proposes the old idea (which appears however a little questionable) that the collapse of the wave function happens at the moment when the information about the interaction between the microsystem and the macrosystem arrives in the observer's brain: according to this view, there would be no collapse until the signal reaches the observer's brain [21]. As regards the question of when precisely a quantum event happens, when precisely properties of subatomic systems become manifest, according to the authors, Rovelli's view seems more interesting. It has

shown that the quantum theory gives a precise answer to this question. Rovelli has found that: (i) a precise (operational) sense can be given to the question of the timing of the measurement; (ii) we can compute the time at which the measurement happens using standard quantum techniques; (iii) the interpretation of the physical meaning of this time is no more problematic than the interpretation of any other quantum result [22]. Rovelli showed that the question “When does the measurement happen?” is quantum mechanical in nature, and not classical. Therefore, its answer must be probabilistic. For example, the sentence “half way through a measurement” would mean that the measurement is just “happened with 1/2 probability”, or “already realized in half of the repetitions of the experiment”. The second idea is that the question “When does the measurement happen?” does not regard the measured quantum system S alone, but rather the coupled system formed by the observed system S and the observer system O. Therefore, the appropriate theoretical setting for answering this question is the quantum theory of the two coupled systems. In more detail, Rovelli has introduced an operator measuring whether or not the measurement has happened. By considering the simple case of a physical system S (for example an electron) that interacts with another physical system O (an apparatus measuring the spin of the electron) and that the interaction between S and O qualifies as a quantum measurement of the variable  $q$  of the system S, if we suppose that  $q$  has only two eigenvalues  $a$  and  $b$ , during the interaction between S and O, the state of the combined system S-O is

$$\psi = c_a |a\rangle \otimes |Oa\rangle + c_b |b\rangle \otimes |Ob\rangle \quad (14)$$

where  $|a\rangle$  and  $|b\rangle$  are the eigenstates of  $q$  corresponding to the eigenvalues  $a$  and  $b$  respectively,  $|Oa\rangle$  and  $|Ob\rangle$  are the states of O that can be identified as “the pointer of the apparatus indicates that  $q$  has value  $a$ ” and “the pointer of the apparatus indicates that  $q$  has value  $b$ ”, respectively. When the combined system S-O is in the state (14), a definite correlation between the pointer variable, with eigenstates  $|Oa\rangle$  and  $|Ob\rangle$  and the system variable, with eigenstates  $|a\rangle$  and  $|b\rangle$ , is established.

For some reason, at some point, we have to (or we can) replace the pure state (14) with a mixed state. Equivalently, we replace (14) with either

$$\psi_a = |a\rangle \otimes |Oa\rangle \quad (15)$$

or

$$\psi_b = |b\rangle \otimes |Ob\rangle \quad (16)$$

where, of course, the probability of having one or the other is  $|c_a|^2$  and  $|c_b|^2$  respectively. If the wave function has collapsed, and the state is either (15) or (16), the correlation between the pointer variable and the system variable is present as well.

Rovelli focuses attention on the question of what we can say about the precise time  $t$  at which the wave function changes from (14) to either (15) or (16) and the quantity  $q$  acquires correspondingly a definite value. In this regard, Rovelli has found that the operator  $M$  which measures the timing of the measurement is defined as the projection operator on the subspace spanned by the two states  $\psi_a$  and  $\psi_b$ :  $M = |\psi_a\rangle\langle\psi_a| + |\psi_b\rangle\langle\psi_b|$ .  $M$  turns out to be a self-adjoint operator on the Hilbert space of the coupled system S-O. It may admit an interpretation as an observable property of the coupled system S-O. In all the eigenstates of  $M$  with eigenvalue 1 the pointer variable correctly indicates the value of  $q$ . In all the eigenstates of  $M$  with eigenvalue 0, it does not. Therefore,  $M$  has the following interpretation:  $M = 1$  means that the pointer (correctly) measures  $q$ .  $M = 0$  means that it does not. Now, when the pointer of the apparatus correctly measures the value of the observed quantity, we say that the measurement has happened. Therefore we can say that  $M = 1$  has the physical interpretation “the measurement has happened”, and  $M = 0$  has the physical interpretation “the measurement has not happened”. By applying standard quantum mechanical rules to this operator, at every time  $t$ , we can compute a precise (although probabilistic) answer to the question whether or not the measurement has happened: the probability that the measurement has happened at time  $t$  is given by relation  $P(t) = \langle\psi(t)|M|\psi(t)\rangle$  where  $\psi(t)$  is the state of the coupled system during the Schrödinger evolution. The probability density  $p(t)$  that the measurement happens between time  $t$  and time  $t+dt$  is

$$p(t) = \frac{d}{dt} \langle\psi(t)|M|\psi(t)\rangle = \langle\psi(t)|[M, H]|\psi(t)\rangle \quad (17)$$

where  $H$  is the total Hamiltonian. For a good measurement in which  $P(t)$  grows smoothly and monotonically from zero to one,  $p(t)$  will be a “bell shaped” curve, defining the time at which the measurement happens, and its quantum dispersion.

Now, in the picture of our model of space and time according to which the fundamental arena of physics is a 3D space and clocks provide a numerical order of events, Rovelli’s results can be read in the following manner. The operator  $M$  can be interpreted as the operator which measures the numerical order of a measurement during the interaction between a subatomic system and an apparatus; the probability density (17) defines the numerical order associated with the actualization of a measurement. Moreover, on the basis of the treatment

made here, one can conclude that the fundamental essence, the fundamental arena of measurement processes is represented by the correlation, in the 3D space, between a physical system and an apparatus and thus by the entangled state (14) in the sense that it is just by starting from this state that one can compute the numerical order corresponding with the actualization of the measured property of the physical system under consideration. The quantum superposition, the quantum entanglement between the measured physical system and the apparatus can be considered the fundamental reality of space in the quantum domain. Now, the crucial point introduced by the authors of this article is that by means of quantum entanglement, in virtue of some fundamental phenomena in which the elapsed clock run for them to happen is zero, the 3D timeless space (where time exists only as a numerical order of material changes) acts as an immediate medium of information transfer between the systems under consideration.

In order to illustrate in detail in what sense a 3D space acts as an immediate medium of information transfer in immediate physical phenomena regarding the quantum domain by means of quantum entanglement, the best way is to consider the classic example of EPR-type experiment given by Bohm [23] in 1951. 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:

$$\psi(\vec{x}_1, \vec{x}_2) = f_1(\vec{x}_1)f_2(\vec{x}_2)\frac{1}{\sqrt{2}}(u_+v_- - u_-v_+) \quad (18)$$

where  $f_1(\vec{x}_1)$ ,  $f_2(\vec{x}_2)$  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 we 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 (18) reduces to the first of its summands:

$$\psi \rightarrow f_1f_2u_+v_- \quad (19).$$

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. This means that as regards spin measurements there are correlations between the two particles. By considering the particles 1 and 2 separately, one can think about a strange influence of one particle onto the other. A measurement on one of the two particles automatically fixes also the state of the other particle, independently of the distance between them. 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<sup>1</sup>.

As we have illustrated through Bohm's example, the surprising fact regarding the quantum entanglement lies in the fact that the results of the measurement of the spin of two particles are 100% correlated, if for both particles we measure the spin along the same direction. According to Bell's theorem, it is not possible to interpret all the correlations between the two particles regarding the spin measurements by assuming that the two particles are born with the relative instructions about how to behave [24]. But then in what way can we interpret the fact that the measurement of a particle defines in what state the other particle is found, independently of the distance? In 1935, after EPR's work, Bohr suggested that the two entangled particles, independently of their distance, continue to constitute an unity, a single system: the two particles have not an autonomous existence. Below we will show that this Bohr's interpretation can receive a natural basis, if space is considered as the medium of information transfers in quantum physics.

According to the previsions of the quantum theory, in EPR-type experiments the transmission of the information has zero numerical order. If the state of the second particle changes instantaneously after the measurement on the first particle, this fact does not imply a transmission of the information at a higher speed than light speed because we can not influence the outcome of the first measurement. According to the authors, the information between the two particles is instantaneous thanks to the medium of space. A 3D space (where time is not a primary physical reality but exists only as a numerical order of material change) can be considered the fundamental medium which can explain the non-local correlations determined by entanglement in Bohm's example. One can say that the state of the particle 2 is instantaneously influenced by the kind of measurements regarding the particle 1 because space acts as an immediate information medium between the two particles.

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<sup>1</sup> It is also important to underline that if one assumes the quantum interference as a fundamental property, independent of space separation of quantum mechanical systems, the non-locality becomes a natural phenomenon.

It is the medium of the 3D space which produces an instantaneous connection between the two particles as regards the spin measurements: by disturbing system 1, system 2 is instantaneously influenced despite the big distance separating the two systems thanks to space which acts as an immediate information medium and puts them in an immediate contact.

It is important to emphasize here that the interpretation of quantum entanglement and non-locality as immediate physical phenomena determined by a timeless 3D space that acts as an immediate information medium appears legitimate in virtue of the fact that quantum entanglement and non-locality cannot be explained by invoking a mechanism of entities that are transmitters of information between the particles under consideration: there is no information signal in the form of a photon or some other particle travelling between particles 1 and 2 of Bohm's example. The time of information transfer between particle 1 and particle 2 is zero [25]. Information between particle 1 and particle 2 has not duration: this suggests that there is a fundamental medium that acts as an immediate information medium. And in this article the point of view suggested by the authors is just that this fundamental medium is a 3D space where time exists only as a numerical order of material change. The 3D space is an immediate information medium that is informing particle 1 about the behaviour of particle 2 and vice versa. It is the 3D space medium which determines an immediate information transfer and allows us to explain why and in what sense, in an EPR experiment, two particles coming from the same source and going away, remain joined by a mysterious link, why and in what sense if we intervene on one of the two particles, also the other feels the effects instantaneously despite the relevant distances separating it [26].

It is important to stress that the idea of the 3D space as a direct, immediate information medium between subatomic particles follows as a natural development from Bohm's quantum potential. As we know, in his classic works of 1952 and 1953 [27, 28], 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 guided by the wave happens in agreement with the law of motion which assumes the following form

$$\frac{\partial S}{\partial t} + \frac{|\nabla S|^2}{2m} - \frac{\hbar^2}{2m} \frac{\nabla^2 R}{R} + V = 0 \quad (20)$$

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

$$Q = -\frac{\hbar^2}{2m} \frac{\nabla^2 R}{R} \quad (21)$$

having the dimension of an energy and containing Planck constant and therefore appropriately defined quantum potential.

The treatment provided by relations (20) and (21) can be extended in a simple way to many-body systems. If we consider a wave function  $\psi = R(\vec{x}_1, \dots, \vec{x}_N, t) e^{iS(\vec{x}_1, \dots, \vec{x}_N, t)/\hbar}$ , defined on the configuration space  $R^{3N}$  of a system of  $N$  particles, the movement of this system under the action of the wave  $\psi$  happens in agreement to the law of motion

$$\frac{\partial S}{\partial t} + \sum_{i=1}^N \frac{|\nabla_i S|^2}{2m_i} + Q + V = 0 \quad (22)$$

where

$$Q = \sum_{i=1}^N -\frac{\hbar^2}{2m_i} \frac{\nabla_i^2 R}{R} \quad (23)$$

is the many-body quantum potential. The equation of motion of the  $i$ -th in the particle, within the limit of big separations, can also be written in the following form

$$m_i \frac{\partial^2 \vec{x}_i}{\partial t^2} = -[\nabla_i Q(\vec{x}_1, \vec{x}_2, \dots, \vec{x}_n) + \nabla_i V_i(\vec{x}_i)] \quad (24)$$

which is a quantum Newton law for a many-body system. Equation (24) shows that the contribution to the total force acting on the  $i$ -th particle coming from the quantum potential, i.e.  $\nabla_i Q$ , is a function of the positions of all the other particles and thus in general does not decrease with distance.

The quantum potential is the crucial entity which allows us to understand the features of the quantum world determined by Bohm's version of quantum mechanics. The mathematical expression of quantum potential shows that this entity does not have the usual properties expected from a classic potential. Relations (21) and (23) tell us clearly that the quantum potential depends on how the amplitude of the wave function varies in the 3D space. The presence of Laplace operator indicates that the action of this potential is space-like, namely creates onto the particles a non-local, instantaneous action. In relations (21) and (23) the appearance of the absolute value 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 (as the equation of motion (24) of the many-body systems shows clearly, 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). This is just the type of behaviour required to explain EPR-type correlations.

If we examine the expression of the quantum potential in the two-slit experiment, we may find that it depends on the width of the slits, their distance apart and the momentum of the particle. In other words, the quantum potential has a contextual nature, namely brings 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 behaviour of the particle. In a double-slit experiment, for example, if one of the two slits is closed the quantum potential changes, and this information arrives instantaneously to the particle, which behaves as a consequence.

Now, the fact that the quantum potential produces a space-like and active information means that it cannot be seen as an external entity in space but as an entity which contains spatial information, as an entity which represents space. On the basis of the fact that the quantum potential has an instantaneous action and contains active information about the environment, one can say that it is space which is the medium responsible for 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 spatial information, is linked to the 3D space.

In virtue of its features, the quantum potential can be considered a geometric entity, the information determined by the quantum potential is a type of geometric information “woven” into space. Quantum potential has a geometric nature just because it has a contextual nature, contains global information on the environment in which the experiment is performed and at the same time it is a dynamical entity just because its information about the process and the environment is active, determines the behaviour of the particles.

In this geometric picture one can say that the quantum potential indicates, contains the geometric properties of space from which the quantum force, and thus the behaviour of quantum particles, derive. Considering the double-slit experiment, the fact that the quantum potential is linked with the width of the slits, their distance apart and the momentum of the particle, namely that brings global information on the environment means that it describes the geometric properties of the experimental arrangement (and therefore of space) which determine the quantum force and the behaviour of the particle. And the presence of Laplace operator (and of the absolute value of the wave function in the denominator)

indicates that the geometric properties contained in the quantum potential determine a non-local, instantaneous action. We can say therefore that Bohm's theory manages to make manifest this essential feature of quantum mechanics, just by means of the geometric properties of space described and expressed by the quantum potential. As regards the geometric nature of the quantum potential and the non-local nature of the interactions in physical space, one can also say, by paraphrasing J. A. Wheeler's famous saying about general relativity, that the evolution of the state of a quantum system changes active global information, and this in turn influences the state of the quantum system, redesigning the non-local geometry of the universe.

In synthesis, according to the authors, in virtue of the space-like action of the quantum potential, the medium of the 3D space has a crucial role in determining the motion and the behaviour of subatomic particles. On the basis of the equations (21) and (23), one can say that it is space which is the medium responsible for the behaviour of quantum particles. One can say that equations (21) and (23) of the quantum potential contain the idea of space as an immediate information medium in an implicit way.

In particular, if we consider a many-body quantum process (such as for example the case of an EPR-type experiment, of two subatomic particles, first joined and then separated and carried away at big distances one from the other), we can say that the 3D physical space assumes the special "state" represented by the quantum potential (23), and this allows an instantaneous communication between the particles under consideration [29]. If we examine the situation considered by Bohm in 1951 (illustrated before) we can say that it is the state of space in the form of the quantum potential (23) 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 a big distance between the two systems thanks to the features of space which put them in an immediate communication.

In synthesis, one can say that in EPR-type experiments the quantum potential (23) makes the 3D physical space an "immediate information medium" between elementary particles. In EPR-type experiments the behaviour of a subatomic particle is influenced instantaneously by the other particle thanks to the 3D space which functions as an immediate information medium in virtue of the geometric properties represented by the quantum potential (23).

However, what makes indeed the 3D space an immediate information medium in EPR-type correlations? If the space that we perceive seems to be characterized by local features, from which fundamental entity or structure the property of the quantum potential to determine the action of the 3D space as an immediate information medium derives? In this regard, according to the authors, it is important to mention that in the recent article *Bohmian split of the Schrödinger*

equation onto two equations describing evolution of real functions, Sbitnev [30] has shown that the quantum potential can be determined as an information channel into the movement of the particles as a consequence of the fact that it determines two quantum correctors into the energy of the particle depending on a more fundamental physical quantity that can be appropriately called “quantum entropy”. This new way of reading Bohmian mechanics can be called as the “entropic version” of Bohmian mechanics or, more briefly, “entropic Bohmian mechanics”. In the case of a one-body system, the quantum entropy is defined by the logarithmic function

$$S_Q = -\frac{1}{2} \ln \rho \quad (25a)$$

where  $\rho = |\psi(\vec{x}, t)|^2$  is the probability density (describing the space-temporal distribution of the ensemble of particles, namely the density of particles in the element of volume  $d^3x$  around a point  $\vec{x}$  at time  $t$ ) associated with the wave function  $\psi(\vec{x}, t)$  of an individual physical system. In the case of a many-body system, the quantum entropy is always defined by the logarithmic function

$$S_Q = -\frac{1}{2} \ln \rho \quad (25b)$$

where here  $\rho = |\psi(\vec{x}_1, \vec{x}_2, \dots, \vec{x}_N, t)|^2$  is the probability density (describing the space-temporal distribution of the ensemble of particles, namely the density of particles in the element of volume  $d^3x$  around a point  $\vec{x}$  at time  $t$ ) associated with the wave function  $\psi(\vec{x}_1, \vec{x}_2, \dots, \vec{x}_N, t)$  of the many-body system under consideration. In the entropic version of Bohmian mechanics, one can assume that the 3D space distribution of the ensemble of particles describing the physical system under consideration generates a modification of the background space characterized by the quantity given by equation (25a) (or (25b)). The quantum entropy ((25a) and (25b)) can be interpreted as the physical entity that, in the quantum domain, characterizes the degree of order and chaos of the vacuum – a storage of virtual trajectories supplying optimal ones for particle movement – which supports the density  $\rho$  describing the space-temporal distribution of the ensemble of particles associated with the wave function under consideration. By introducing the quantum entropy, for one-body systems, the quantum potential can be expressed in the following convenient way

$$Q = -\frac{\hbar^2}{2m} (\nabla S_Q)^2 + \frac{\hbar^2}{2m} (\nabla^2 S_Q) \quad (26).$$

and we obtain the following equation of motion for the corpuscle associated with the wave function  $\psi(\vec{x}, t)$ :

$$\frac{|\nabla S|^2}{2m} - \frac{\hbar^2}{2m} (\nabla S_Q)^2 + V + \frac{\hbar^2}{2m} (\nabla^2 S_Q) = -\frac{\partial S}{\partial t} \quad (27)$$

which provides an energy conservation law where the term  $-\frac{\hbar^2}{2m} (\nabla S_Q)^2$  can be interpreted as the quantum corrector of the kinetic energy  $\frac{|\nabla S|^2}{2m}$  of the particle, while the term  $\frac{\hbar^2}{2m} (\nabla^2 S_Q)$  can be interpreted as the quantum corrector of the potential energy  $V$ .

In the case of many-body systems, the quantum potential is given by the following expression

$$Q = \sum_{i=1}^N \left[ -\frac{\hbar^2}{2m_i} (\nabla_i S_Q)^2 + \frac{\hbar^2}{2m_i} (\nabla_i^2 S_Q) \right] \quad (28)$$

and the equation of motion is

$$\sum_{i=1}^N \frac{|\nabla_i S|^2}{2m_i} - \sum_{i=1}^N \frac{\hbar^2}{2m_i} (\nabla_i S_Q)^2 + V + \sum_{i=1}^N \frac{\hbar^2}{2m_i} (\nabla_i^2 S_Q) = -\frac{\partial S}{\partial t} \quad (29)$$

which provides an energy conservation law where the term  $-\sum_{i=1}^N \frac{\hbar^2}{2m_i} (\nabla_i S_Q)^2$  can be interpreted as the quantum corrector of the kinetic energy of the many-body system, while the term  $\sum_{i=1}^N \frac{\hbar^2}{2m_i} (\nabla_i^2 S_Q)$  can be interpreted as the quantum corrector of the potential energy.

On the ground of Sbitnev's results, it becomes thus permissible the following reading of the quantum potential and of the energy conservation law in quantum mechanics. The quantum potential derives from the quantum entropy describing the degree of order and chaos of the background space (namely the modification in the background space) produced by the density of the ensemble of particles associated with the wave function under consideration. And, on the basis of equations (27) and (29), we can say that the quantum entropy determines two quantum correctors in the energy of the physical system under consideration (of the kinetic energy and of the potential energy respectively) and without these two quantum correctors (linked just with the quantum entropy) the total energy of the system would not be conserved. Moreover, in this entropic approach to Bohmian mechanics, the classical limit can be expressed by the conditions

$$(\nabla S_Q)^2 \rightarrow (\nabla^2 S_Q) \quad (30)$$

for one-body systems and

$$\left(\nabla_i S_Q\right)^2 \rightarrow \left(\nabla_i^2 S_Q\right) \quad (31)$$

for many-body systems. The quantum dynamics will approach the classical dynamics when the quantum entropy satisfies conditions (30) (for one-body systems) or (31) (for many-body systems) which can be considered as the expression of the correspondence principle in quantum mechanics.

With the introduction of the quantum entropy ((25a) for one-body systems and (25b) for many body systems) which leads to the energy conservation law (equation (27) for one-body system and equation (29) for many-body system), now new light can be shed on the interpretation of the action of the 3D space as an immediate information medium in EPR-type correlations. In fact, on the basis of equation (29), one can say that the action of the 3D space as an immediate information medium derives just from the two quantum correctors to the energy of the system under consideration, namely from the quantum corrector to the potential energy  $\sum_{i=1}^N \frac{\hbar^2}{2m_i} (\nabla_i^2 S_Q)$  and the quantum corrector to the kinetic energy  $-\sum_{i=1}^N \frac{\hbar^2}{2m_i} (\nabla_i S_Q)^2$  (while the other two terms  $\sum_{i=1}^N \frac{|\nabla_i S|^2}{2m_i}$  and  $V$  on the right-hand of equation (29) determine a local feature of space). The feature of the quantum potential to make the 3D space an immediate information channel into the behaviour of quantum particles derives just from the quantum entropy. In other words, one can see that by introducing the quantum entropy given by equation (25b), it is just the two quantum correctors to the energy of the system under consideration, depending on the quantity describing the degree of order and chaos of the vacuum supporting the density  $\rho$  (of the particles associated with the wave function under consideration) the fundamental element, which at a fundamental level produces an immediate information medium in the behaviour of the particles in EPR-type experiments. The space we perceive seems to be characterized by local features because in our macroscopic domain the quantum entropy satisfies conditions (30) or (31).

In synthesis, in the entropic version of Bohmian mechanics, one can say that the quantum entropy, by producing two quantum corrector terms in the energy, can be indeed interpreted as a sort of intermediary entity between space and the behaviour of quantum particles, and thus between the non-local action of the quantum potential and the behaviour of quantum particles. The introduction of the quantum entropy (given by equation (25a) or (25b)) as the fundamental entity that determines the behaviour of quantum particles leads to an energy conservation law in quantum mechanics (expressed by equations (27) and (29)) which lets us realize what makes indeed the 3D space an immediate information medium in EPR-type

correlations, which in turn lets us realize from which property of the quantum potential one can derive the action of the 3D space as an immediate information medium. The ultimate source, the ultimate visiting card which determines the action of the 3D space as an immediate information medium between quantum particles is a fundamental vacuum defined by the quantum entropy ((25a) or (25b)). The quantum entropy, by producing two quantum corrector terms in the energy, is the fundamental element which gives origin to the non-local action of the quantum potential.

Now, as regards the instantaneous communication between quantum particles in EPR-type experiments and the role of the 3D space as a direct information medium between them, 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. In other words, the instantaneous communication between two particles in EPR experiment 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 happens and – we can say – always owing to space which functions as an immediate information medium. Moreover, if we imagine to film the process of an instantaneous communication between two subatomic particles in EPR-type experiments backwards, namely inverting the sign of time, we should expect to see what really happened. Inverting the sign of time, we have however no guarantee that we obtain something that corresponds to what physically happens. Although the quantum potential ((21) for one-body systems and (23) for many-body systems) has a space-like, an instantaneous action, however it comes from Schrödinger equation which is not time-symmetric and therefore its expression cannot be considered completely satisfactory just because it can meet problems inverting the sign of time.

On the basis of these considerations, in order to interpret in the correct way, also in symmetric terms in exchange of  $t$  for  $-t$ , the instantaneous communication between subatomic particles and thus the interpretation of 3D space as an immediate information medium, in quantum theory in line of principle a symmetry in time is required. For this reason the authors of this article have recently introduced a research line based on a symmetrized version of the quantum potential. The symmetrized quantum potential can explain a symmetric and instantaneous communication between subatomic particles and thus can be considered as a better candidate for the state of the 3D space as an immediate information medium in EPR-type experiments (or, more generally, in each immediate physical phenomenon). In the case of a system of  $N$  particles the symmetrized quantum potential assumes the form

$$Q = \sum_{i=1}^N -\frac{\hbar^2}{2m_i} \begin{pmatrix} \nabla_i^2 R_1 \\ R_1 \\ -\nabla_i^2 R_2 \\ R_2 \end{pmatrix} \quad (32)$$

where  $R_1$  is the absolute value of the wave-function  $\Psi = R_1 e^{iS_1/\hbar}$  describing the forward-time process (solution of the standard Schrödinger equation) and  $R_2$  is the absolute value of the wave-function  $\phi = R_2 e^{S_2/\hbar}$  describing the time-reverse process (solution of the time-Schrödinger equation). On the basis of equation (32), we can explain non-local correlations in many-body systems – and thus EPR experiments – in the correct way (that is, also if one would imagine to film back the process of these correlations). The symmetrized quantum potential (32) can be considered the most appropriate candidate to provide a mathematical reality to a 3D space intended as a direct information medium [31]. In fact, the symmetrized quantum potential is characterized by two components, the one regarding the forward-time process, the other regarding the time-reverse process. The first component of the symmetrized quantum potential,

$$Q_1 = \sum_{i=1}^N -\frac{\hbar^2}{2m_i} \frac{\nabla_i^2 R_1}{R_1} \quad (33),$$

which is related to the forward-time process and coincides with the original Bohm's quantum potential, is the real physical component which produces observable effects in the quantum world. 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 [32, 33]). The first component (33) expresses the instantaneous action on quantum particles and thus the immediate action of space on them. The second component,

$$Q_2 = \sum_{i=1}^N \frac{\hbar^2}{2m_i} \frac{\nabla_i^2 R_2}{R_2} \quad (34),$$

is introduced to reproduce in the correct way the time-reverse process of the instantaneous action and thus it guarantees that the quantum world can be interpreted correctly with the idea of space as an immediate information medium if one would imagine to film the process backwards: it must be introduced in order

to recover a symmetry in time in quantum processes, to interpret in the correct way quantum processes if one would imagine to film that process backwards. The opposed sign of the second component with respect to the physical first component (that is, with respect to the original Bohm's quantum potential) can be interpreted as a consequence of the idea of the measurable time as a measuring system of the numerical order of material change: the mathematical features of the second component of the symmetrized quantum potential imply that it is not possible to go backwards in the physical time intended as the numerical order of physical events.

Both the components (33) and (34) of the symmetrized quantum potential can be considered as physical quantities deriving from the quantum entropy (25b). The first component can be expressed as

$$Q = \sum_{i=1}^N \left[ -\frac{\hbar^2}{2m_i} (\nabla_i S_{Q1})^2 + \frac{\hbar^2}{2m_i} (\nabla_i^2 S_{Q1}) \right] \quad (35),$$

while the second component can be expressed as

$$Q = \sum_{i=1}^N \left[ \frac{\hbar^2}{2m_i} (\nabla_i S_{Q2})^2 - \frac{\hbar^2}{2m_i} (\nabla_i^2 S_{Q2}) \right] \quad (36),$$

where  $S_{Q1} = -\frac{1}{2} \ln \rho_1$  is the quantum entropy defining the degree of order and chaos of the vacuum for the forward-time processes (where  $\rho_1 = |\psi(\vec{x}_1, \vec{x}_2, \dots, \vec{x}_N, t)|^2$ ,  $\psi(\vec{x}_1, \vec{x}_2, \dots, \vec{x}_N, t) = R_1 e^{-iS_1/\hbar}$  being the forward-time many-body wave function, solution of the standard Schrödinger equation) and  $S_{Q2} = -\frac{1}{2} \ln \rho_2$  is the quantum entropy defining the degree of order and chaos of the vacuum for the time-reverse processes (where  $\rho_2 = |\phi(\vec{x}_1, \vec{x}_2, \dots, \vec{x}_N, t)|^2$ ,  $\phi(\vec{x}_1, \vec{x}_2, \dots, \vec{x}_N, t) = R_2 e^{-S_2/\hbar}$  being the time-reverse many-body wave function, solution of the time-reversed Schrödinger equation). The energy conservation law for the forward-time process is

$$\sum_{i=1}^N \frac{|\nabla_i S_1|^2}{2m_i} - \sum_{i=1}^N \frac{\hbar^2}{2m_i} (\nabla_i S_{Q1})^2 + V + \sum_{i=1}^N \frac{\hbar^2}{2m_i} (\nabla_i^2 S_{Q1}) = -\frac{\partial S_1}{\partial t}, \quad (37)$$

while the energy conservation law for the reversed-time process is

$$\sum_{i=1}^N \frac{|\nabla_i S_2|^2}{2m_i} + \sum_{i=1}^N \frac{\hbar^2}{2m_i} (\nabla_i S_{Q2})^2 - V - \sum_{i=1}^N \frac{\hbar^2}{2m_i} (\nabla_i^2 S_{Q2}) = -\frac{\partial S_2}{\partial t} \quad (38).$$

On the basis of its mathematical features, the symmetrized quantum potential

implies that in the quantum domain a timeless 3D space has a crucial role in determining the motion of a subatomic particle because the symmetrized quantum potential produces a like-space and instantaneous action on the particles under consideration and contains active information about the environment and, on the other hand, implies the concept of time as a numerical order of material change. In EPR-type experiments (and, more generally, in all immediate physical phenomena regarding the quantum domain) the 3D timeless space acts as an immediate information medium in the sense that the first component of the symmetrized quantum potential makes physical space an “immediate information medium” which keeps two elementary particles in an immediate contact (while the second component of the symmetrized quantum potential reproduces, from the mathematical point of view, the symmetry in time of this communication and the fact that time exists only as a numerical order of material change). We can call this peculiar interpretation of quantum non-locality as the “immediate symmetric interpretation” of quantum non-locality.

## 5. CONCLUSIONS

This article shows that a 3D space where time  $t$  is exclusively a numerical order of material changes can be considered a fundamental arena of physical processes. At a fundamental level, we live in a universe where time measured by clocks exists exclusively as a numerical order of material changes. Non-local correlations in EPR-type experiments are carried directly by the 3D space, the numerical order  $t$  of quantum entanglement is zero in the sense that the 3D space functions as an immediate information medium. The action of the 3D space as an immediate information medium derives from the quantum entropy describing the degree of order and chaos of the vacuum supporting the density of the particles associated with the wave function under consideration. The symmetrized quantum potential characterized by the two components (where the first component coincides with the original Bohm’s quantum potential and the second component is endowed with an opposed sign with respect to it) seems to be the most appropriate candidate to represent the mathematical state of the 3D space as an immediate information medium between subatomic particles that accounts for entanglement and non-locality (and more generally, for all immediate physical phenomena in the quantum domain).

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