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What is the Actual Behaviour of the Electron? From Bohm's Approach to the Transactional Interpretation to A Three-Dimensional Timeless Non-Local Quantum Vacuum

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Abstract: Bohm's quantum physics vision can be considered the real epistemological foundation of the idea of a unified quantum vacuum as a fundamental medium subtending the observable forms of matter, energy and space-time. By assuming non-locality as the ultimate visiting card of quantum processes, it leads directly to the transactional interpretation and then to the idea of a three-dimensional timeless non-local quantum vacuum. In this picture, the behaviour of a subatomic particle (such as the electron) in a given quantum experiment derives from elementary processes of creation/annihilation of quanta corresponding to elementary fluctuations of the energy density of the three-dimensional timeless non-local quantum vacuum.

Keywords: Bohm's quantum physic; Epistemology; Non-local Quantum Vacuum
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1 Introduction

Quantum physics, in its modern formulation, has about 90 years. Although at the beginning it was a very speculative theory, in the following decades a lot of experiments have confirmed its predictions in an excellent way, with a incredibly high precision. This turned out very important in order to convince the scientific community that quantum mechanics is correct, till the point that today nobody sees the necessity to develop a new theory that replaces quantum mechanics.

However, since its birth, quantum mechanics has created many interpretative problems in regard to what it says about the world. On the basis of experimental results,

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quantum systems seem to live an exotic, indefinite realm, contrary to what happens to macroscopic systems of our everyday experience, despite they are ultimately built out starting from quantum systems. Quantum theory is formulated in such a way that implies a dramatic boundary between classical domain and quantum domain. What does it happen when we move to lower and lower scales? In particular, at what point can one say that physical reality generate the exotic features of the microscopic world? How do atomic and subatomic particles behave? Despite the extraordinary progresses achieved in high energy physics and in cosmology after world war two, even today a well defined and completely satisfactory answer to these simple questions does not exist [1, 2].

As regards the geometry of the physical world, one can say that quantum physics yields more spread scenarios than those offered by every previous physical theory. In particular, the most fundamental and intriguing element which emerges from the quantum formalism lies in the fact that subatomic particles are non-locally connected and can be in entangled states. The non-local correlations between subatomic particles which characterize EPR-type experiments turn out to be inexplicable and understandable inside a classical picture. In the Copenhagen interpretation owed to Bohr, Heisenberg and their followers, non-locality emerges indeed as an unexpected host which lies behind the purely probabilistic interpretation of the wave function and the mechanism of "casuality" associated with it. However, on the basis of the experimental results of many authors (such as those of A. Aspect and A. Zeilinger, just to name a few), one has to acknowledge that non-locality is the ultimate visiting card of the geometry of quantum physics and it should be introduced from the very beginning within the theory structure as a fundamental principle. The experimental results suggest that quantum non-locality must be considered as the essential property which is at the basis of the behaviour of subatomic particles and of the geometry of the quantum world [3, 4].

The non-local correlations characterizing the behaviour of subatomic particles do not transport energy, for this reason they do not violate the laws of relativity. In other words, quantum non-locality turns out to be compatible with the existence of a limit speed: the quantum formalism cannot be used to send superluminal signals. This condition defines a sort of "pacific coexistence" between relativity and quantum physics [5]. Nonetheless, it becomes natural to put ourselves the following fundamental question: is the space-time model used in relativity appropriate to describe the peculiarities of the geometry of the quantum world? The problem of reconciling the classical image of Einstein's space-time and quantum non-locality becomes therefore to build a dynamic model of the space-time background in which the quantum processes also find a place and to characterize the geometrical properties of this background, in other words to develop a quantum geometrodynamics.

Despite 20^{th} century theoretical physics opened important perspectives in the exploration of new territories (such as the meaning of matter at the Planck scale and the role of the quantum information), it is characterized by significant foundational problems which the inner unity of physics knowledge depend on. In the light of the developments of theoretical physics during last century, what must be considered the real, fundamental arena of physical processes? What is the real background of physics which determines and rules the behaviour of matter? What is space? What is the geometry that rules physical processes? What is matter? What is the meaning of "motion" of a subatomic particle such as, for example, the electron? Does nature play the same game on different scales? Are there only formal analogies between the different descriptive levels of physical reality or is there a deeper meaning? These are some of the foundational questions that one must face in order to find a unifying picture and synthesis in physics. We need to find a new answer to these questions – different from Newton's answer – which takes into account what we have learned about the world with the building blocks of contemporary physics, namely quantum mechanics, special relativity and general relativity and, at the same time, involves also significant changes of perspectives able to provide a unifying picture and let us realize matter and space-time at the fundamental level.

Assuming non-locality as the ultimate visiting card of quantum mechanics, one can think that there are two possible ways in order to build a fundamental theory which describes the geometrodynamics and the arena of physical processes, exploring the actual behaviour of matter at the fundamental level:

a) the quantum geometry is assumed as primary and non-local, and therefore it is necessary to introduce additional hypotheses about its deep structure, or

b) the space-time manifold must be considered an emergence of the deepest processes situated at the level of quantum gravity. In this regard, one can mention here, at least, Sacharov's original proposal of deducing gravity as "metric elasticity" of quantum vacuum in which the action of space-time is interpreted as the effect of quantum fluctuations of the vacuum in a curved space [6], Haisch's and Rueda's model regarding the interpretation of inertial mass and gravitational mass as effects of an electromagnetic quantum vacuum [7], Puthoff's polarizable vacuum model of gravitation [8] and the most recent one by Consoli on ultra-weak excitations in a condensed manifold as a model for gravity and Higgs mechanism [9].

According to these approaches, the entire connected and local structure of both space-time and quantum information can be seen as the explicit order of a hidden, implicit order, in other words a quantum vacuum which acts as a "fabric of reality" at a sub-quantum level, fundamentally discrete and non-commutative [10]. In fact, a crucial consequence of contemporary quantum field theories (such as the quantum electrodynamics, the Weinberg-Salam-Glashow theory of electroweak interactions and the quantum chromodynamics of strong interactions) is constituted by the existence of a unified quantum vacuum as a fundamental medium subtending the observable forms of matter, energy and space-time. In the light of the predictions of quantum field theories, the notion of an "empty" space devoid of any physical properties can be replaced with that of a quantum vacuum state, defined to be the ground (lowest energy density) state of a collection of quantum fields, which exhibits zero-point fluctuations everywhere in space giving rise to an enormous vacuum energy density. These quantum field theories imply that various contributions to the vacuum energy density exist: the fluctuations characterizing the zero-point field, the fluctuations characterizing the quantum chromodynamic level of subnuclear physics, the fluctuations linked with the Higgs field, as well as perhaps other contributions from possible existing sources outside the Standard Model (for instance, Grand Unified Theories, string theories, etc. . .). On the other hand, there is no structure within the Standard Model which suggests any relations between the different contributions to the quantum vacuum energy density, and it is therefore customary to assume that the total vacuum energy density is, at least, as large as any of these individual contributions. As regards the role of the different contributions to the vacuum energy density, the reader can find a detailed analysis, for example, in the paper [11] by Rugh and Zinkernagel who studied the connection between the vacuum concept in quantum field theory and the conceptual origin of the cosmological constant problem, and in the paper [12] by Timashev who examined the possibility of considering the physical vacuum as a unified system governing the processes taking place in microphysics and macrophysics, which manifests itself on all space-time scales, from subnuclear to cosmological.

In this paper, in order to face the foundational questions listed above, we will explore a model of a three-dimensional (3D) timeless non-local quantum vacuum whose most fundamental properties are processes of creation/annihilation of quanta corresponding to changes and fluctuations of the energy density. We will explore how the idea of a 3D timeless non-local quantum vacuum allows us to interpret the real background of physics as well as the meaning of "motion" of a subatomic particle such as, for example, the electron. We will see furthermore how our model faces the problem of the emergence of quantum mechanics and of the existence of different levels of physical reality: whether nature plays the same game on different scales and if there are there formal analogies between the different descriptive levels of physical reality or there is a deeper meaning.

This paper is structured in the following manner. In chapter 2 we will show how Bohm's approach can be considered the starting point to develop a 3D timeless non-local quantum vacuum. In chapter 3 we will see how non-locality can be formalized and described in terms of transactions. In chapter 4 we will analyse how the transactional view leads directly to a 3D timeless non-local quantum vacuum. In chapter 5 we will study the behaviour of subatomic particles inside the 3D timeless non-local quantum vacuum. Finally, in chapter 6 we will explore the perspectives introduced by the model of the 3D timeless non-local quantum vacuum towards an unifying picture of gravity and quantum behaviour.

2 Bohm's View as the Epistemological Foundation to Develop a Three-dimensional Timeless Non-Local Quantum Vacuum

The fundamental starting-point as well epistemological foundation to develop a 3D timeless non-local quantum vacuum can be considered the David Bohm quantum physics vision.

As well known, Bohm's view introduces important and relevant perspectives into the understanding of the exotic features of the microscopic world and of the behaviour of subatomic particles. It suggests a way of treating subatomic processes which is simpler with respect to the Copenhagen interpretation allowing the reopening of many questions (which were considered closed or forever "paradoxical" inside the standard view). What naturally results from Bohm's approach is a theory, predictably equivalent to quantum mechanics, which can provide a causal completion to quantum mechanics and explain the quantum behaviour of matter remaining faithful to the principle of causality and the motion dogma, which not only accommodates, but provides the simplest known explanation for the quantum formalism (including the Born rule, the Heisenberg uncertainty relation, the representation of dynamical variables as Hilbert space operators, and so on). Bohm's interpretation of quantum mechanics reproduces all the empirical results of quantum theory and at the same time has the merit to describe atomic and subatomic processes without ascribing a crucial role to the observer and to recover some causality also in the microscopic world that is so seen as a world in which quantum particles have precise trajectories [1, 2, 13, 14].

As regards the interpretation of non-relativistic quantum mechanics proposed by Bohm, a great deal of confusion exists about what Bohm was saying exactly when he first published his 1952 papers. Many discussions about Bohm's ideas in these two papers assume that they represented some kind of definitive theory. As shown clearly by Hiley in the recent article *Some remarks on the evolution of Bohm' proposals for an alternative to standard quantum mechanics* [15], the misunderstandings about Bohm's original ideas, grew after the appearance of the term "bohmian mechanics" in a 1992 paper of Dürr, Goldstein and Zanghì [16]. However, it must be emphasized that, in his classic works of 1952, Bohm never used the term mechanics: in these two papers Bohm's intention was not to find a classical order based on a deterministic mechanics from which the quantum formalism would be derived. Indeed the content of his book *Quantum Theory* published in 1951 [17], which gives an exhaustive account of the orthodox view of the theory, already shows the seeds of how radical a change Bohm thinks is needed in order to begin to understand the structure that underlies the quantum formalism. By reading that book one can see easily in Bohm's ideas the need to go beyond mechanical ideas. In the section of this book titled 'The need for a non-mechanical description', Bohm writes "....the entire universe must, in a very accurate level, be regarded as a single indivisible unit in which separate parts appear as idealisations permissible only on a classical level of accuracy of the description. This means that the view of the world as being analogous to a huge machine, the predominant view from the sixteenth to nineteenth century, is now shown to be only approximately correct. The underlying structure of matter, however, is not mechanical" [17].

The mathematical formalism suggested by Bohm in his 1952 papers merely show that an alternative view, that attributes definite properties to individual particles, is possible without radically changing the formalism and altering the predictions. He was not offering these proposals as the final definitive interpretation of the quantum formalism in the non-relativistic domain. On the other hand, throughout the papers he stresses that his approach opens up possibilities of modifying the formalism in ways that could not be possible in the standard interpretation, that could expect something deeper.

As shown clearly also by Hiley in [15], the fundamental key element which shows that Bohm's 1952 approach was not mechanical is the quantum potential. In his 1952 papers, Bohm showed that, in virtue of the mathematical features of the quantum potential, the whole environment determines the properties of the individual particles and their relationship. In Bohm's view, the quantum potential implies a universal interconnection of things that could no longer be questioned. What one can conclude from the analysis of Bohm's 1952 papers is that the quantum potential enables the global properties of quantum phenomena to be focused on the particle aspect, where the 'particle' is not independent of the background. In this regard, the ultimate visiting card of Bohm's work has been the crucial role of non-locality to be introduced *ab initio* in the structural corpus of the physical theory, and the quantum potential, even in the plurality of the mathematical treatments, is in the core of such structure, the non-local *trait d'union* between the post-classical features of quantum physics and the most advanced perspectives of field theory [18, 2]. In the last part of his life, Bohm proposed therefore the revolutionary idea that quantum non-locality does not look like a field at all, but it is "written" in the informational structure of a pre-space that Bohm-Hiley called "Implicate Order". This deeper descriptive level of physical reality is revealed only partially, depending on the information the observer chooses to extract from the system, and gives to quantum mechanics its characteristic "contextuality" [19]. In this way, Bohm's approach of implicate order someway allows the recovering of the old Bohr complementarity, now in terms not of something "elusive" and the "uncertain" role of the observer, but of the deep logic of the physical world and the non-commutative relation between system and environment. The theory of Implicate/Explicate order is the first real attempt to realize the J. A. Wheeler program of *It from Bit* (or *QBit*), the possibility to describe the emergent features of space-time-matter as expressions, constrained and conveyed, of an informational matrix "at the bottom of the world" [20].

According to the author, the real starting point and epistemological foundation of the idea of a 3D timeless non-local quantum vacuum can be drawn from the following excerpt of Bohm's "duel" with M. Pryce, a defender of the orthodox vision, broadcasted by BBC in 1962 (excerpt which shows clearly that Bohm's ideas are considerably different from classical and post-classical ones): "We wondered what actually an electron does. What should it do while it passes from the source to the slit? That's the point. Well, I could propose, for example, that the electron is not a particle in the sense it is currently meant, but an event. I assume such event happens in a generic medium – a "field" – we can suppose in this field there's an impulse. A wave moves forward and converges in a point so producing a very strong impulse and then diverges and scatters away. Let's imagine these impulses in a series all reaching a line there producing a series of intense pulses. The impulses will be very close one to the other, and so they will look like a particle. In most cases, all that will behave just like a particle and will behave differently when goes through the two slits, because each impulse will come out according to the way the incident wave passes the slits. The result is that we are looking at something it's neither a wave nor a particle. If you wonder how the electron has actually passed the slit and if it has really passed one slit or the other, I would reply that probably is not that kind of thing which can pass a slit or the other one. Actually, it is something which forms and dissolves continuously and that can be the way it really acts."[21]. As regards the double slit experiment, these last two sentences provide the real most ultimate, crucial key in order to throw new light as regards the problem of the meaning of "motion" of a subatomic particle, of the existence of different descriptive levels of physical reality and thus of the possible deeper origin, at a fundamental level, of physical processes. One can say that the electron intended as a wave or a corpuscle (satisfying the well known laws of quantum theory) has not a primary physical existence but its "physical appearance" actually emerges from more elementary processes of formation and dissolving of quanta of an informational arena. The idea of a fundamental quantum vacuum (in particular, in our model, of a fundamental 3D timeless non-local quantum vacuum) as the ultimate arena of the universe, as the ground (lowest energy density) state of a collection of quantum fields, which exhibits zero-point fluctuations corresponding to elementary processes of creation/annihilation, somewhat draws inspiration from these two sentences of Bohm's 1962 words at BBC. In this regard, the key idea is to introduce Bohm's quantum potential into a 3D isotropic quantum vacuum characterized by a Planckian metric and defined by elementary processes of creation/annihilation of quanta corresponding to Chiatti's and Licata's transactions.

3 From Bohm's View to Kastner's Possibilist Transactional Interpretation and Chiatti's and Licata's Approach about Transactions

Once one realizes that each subatomic particle, such as the electron, is something which forms and dissolves continuously and thus that its behaviour derives from fluctuations corresponding to elementary processes of creation/annihilation of quanta of an informational vacuum, there is the problem to describe mathematically and characterize conceptually this ultimate vacuum. Assuming non-locality as a fundamental feature of this vacuum, a first step in this regard could be to consider the possibilist transactional approach recently proposed R. Kastner in the references [22-25]. The transactional interpretation was originally introduced by John G. Cramer in a series of papers in the 1980s [26-29] by inspiring to previous theories of Wheeler-Feynman and of Hoyle-Narlikar. According to Cramer's approach, the behaviour of a subatomic particle such as the electron is a time-symmetric process, in which one has an "absorber" which generates confirmation waves in response to an emitted offer wave: a system emits a field in the form of half-retarded, half-advanced solutions to the wave equation, and the response of the absorber combines with that primary field to create a process that transfers energy from the emitter to the absorber. Cramer's theory leads to a definition of a vacuum which gives form to the anticipated waves; these inform a particle about the global situation in its space-time region and in this way one can reproduce the quantum behaviours, and in particular explain EPR-type experiments, in terms of information – the transaction events – coming from the future owed to the relativistic nature of the vacuum.

In the recent papers [22-25], Ruth Kastner extended Cramer's approach into a more general and fundamental theory, the possibilist transactional interpretation, which can explain the nature of the process leading to an actualized transaction. In Kastner's approach, space-time is not a pre-existing substance, a structured container for events, but rather unfolds as an emergent manifold from a more fundamental collective structure, a "pre-spacetime" characterized by "transactional processes" (constituted by emission and absorption of quanta) involving de Broglie waves. In the picture proposed by Kastner, the behaviour of a subatomic particle such as the electron derives from realized transactions resulting in transfers of energy from an emitter to an observer, which must be considered as pre-spacetime objects at the micro-level. In Kastner's view, the transactions are processes that somewhat transcend the space-time structure, in other words are the expression of the non-local feature of the processes characterizing subatomic particles. Each quantum particle emerges from actualizations of transactions, and thus from emissions and absorptions of quanta, giving rise to the related events comprising the space-time arena. The actualization of a transaction is an a-spatiotemporal process; it is the coming into being of an event (actually two linked events, the emission and the absorption of quanta).

In Kastner's possibilist transactional approach, the apparent four-dimensional space-time universe we perceive is not something "already there", there is no "space-time" without actualized transactions; rather, space-time crystallizes from an indeterminate (but real) non-local pre-spacetime of dynamical possibility. Kastner's view implies that, if one studies the evolution of a subatomic particle in a given experiment, only the "now" is the fundamental empirical realm and that the changing properties of the physical system under consideration are associated with electromagnetic signals that transfer energy from what we are observing to our sense organs (by way of actualized transactions). The "now" is defined by a spatial coordinate (or, in a relational view of space-time, the object(s) with which we are currently in direct contact) and any light signals that have reached our eyes from other objects. According to the possibilist transactional interpretation, what is fundamental in the temporal sense is just the now, which changes. The now, and thus being is the ultimate, primary reality of the universe, and the description of the evolution of the particle in the time index is just a way of recording the changes of the now. In other words, one deals here with a sort of "growing universe" theory of time; the past grows and continues to become actualized as it falls away from the present. As regards the fundamental arena of the physical processes, one can say that in Kastner's approach the origin of the time of our common experience (and thus of space-time) is contained in matter, whose behaviour in turn emerges from non-local transactional processes resulting in transfers of energy from an emitter to an observer.

Once one arrives to realize that the non-local behaviour of subatomic particles can be seen as something that derives from transactions – involving de Broglie waves and resulting in transfers of energy from an emitter to an observer – which must be considered as pre-spacetime objects at the micro-level, the next fundamental step is to describe mathematically and characterize conceptually the fundamental, ultimate informational vacuum given by the network of these transactional processes. In this regard, according to the author of this paper, the crucial point is represented by the approach of the archaic vacuum developed by Chiatti and Licata in the references [30-33].

In Chiatti's and Licata's model, the vacuum, besides to be an eigenstate of minimal energy, is the network of all the possible transactions of the field modes in an "undivided oneness" and it must be considered as a radical non-local and event-symmetric state. Chiatti's and Licata's approach of transactions implies that the physical vacuum as a fundamental arena of the universe is an archaic, atemporal manifold that constrains and conveys the dynamical processes we observe in nature. Chiatti's and Licata's approach is based on the idea that the only truly existent "things" in the physical world are the events of creation and destruction (or, in other words, physical manifestation and demanifestation) of certain qualities [30]. Such properties' measurement is all that we know of the physical world from an operational view point [31]. In this picture, any other construction in physics – like the continuous space-time notion itself or the evolution operators – has the role to causally connect the measured properties: they are "emergent" with respect to the network of events. In the language of quantum field theory the events of creation and destruction are the "interaction vertices", while the different sets of manifested/demanifested qualities in the same vertex are the "quanta".

From a theoretical point of view, the probability of the occurrence of a creation/destruction event for a quantum Qin a point event $x$is linked with the probability amplitude $\psi_Q(x)$, which can be a spinor of any degree. Each component $\psi_{Q,i}(x)$ of this spinor satisfies the Klein-Gordon quantum relativistic equation

$$\left(-\hbar^2\partial^\mu\partial_\mu + m^2c^2\right)\psi_{Q,i}(x) = 0, \tag{1}$$

where $\hbar$ is Planck's reduced constant and $m$is the mass of the quantum. At the non-relativistic limit, this equation becomes a pair of Schrodinger equations [34]:

$$-\frac{\hbar^2}{2m}\nabla^2\psi_{Q,i}(x) = i\hbar\frac{\partial}{\partial t}\psi_{Q,i}(x) \text{ for creation events} \tag{2}$$

$$-\frac{\hbar^2}{2m}\nabla^2\psi_{Q,i}(x) = -i\hbar\frac{\partial}{\partial t}\psi^*_{Q,i}(x) \text{ for destruction events.} \tag{3}$$

The first equation has only retarded solutions, which classically correspond to a material point with impulse $\mathbf{p}$ and kinetic energy E = $\mathbf{p}\bullet\mathbf{p}/2m>0$. The second equation has only advanced solutions, which correspond to a material point with kinetic energy E=-$\mathbf{p}\bullet\mathbf{p}/2m<0$. Thus there are no true causal propagations from the future. From the point of view of the dynamical laws for the probability amplitudes of these events, the creation of quality $Q$is associated with the initial condition for $\psi_{Q,i}(x)$ in equation (2); the destruction of quality $Q$is associated with the "initial", actually the final, condition for $\psi^*_{Q,i}(x)$ in equation (3).

More generally speaking, in this approach the transactions can be defined in the following way. One has at $t = t_1$ the event of the creation-destruction of a quality

$Q(|\rangle\langle Q|)$ and at $t = t_2$ the event of the creation-destruction of a quality $R(|\rangle\langle R|)$. These two processes are linked by a time evolution operator Swhich acts in the following way: $|\rangle$ is transported from Sinto $|\rangle?\rangle$ and projected onto $\langle R|$, $|\rangle$ is transported by S^+ into $|\rangle?\rangle$ and projected onto $\langle Q|$. The amplitudes product $\langle R| S |\rangle \langle Q| S^+ |\rangle = |\langle R| S |\rangle|^2$ is immediately obtained, which is the probability of the entire process. Moving to the representation of the coordinates, by substituting bras and kets with wavefunctions, we once again obtain as a particular case the result already seen with the non-relativistic expressions (2) and (3). Here, the propagation S^+ is as "real" as the S, in the sense that the initial condition $|\rangle$ and the final one $\langle R|$ are connected in a non-local way, in the light of the well-known non-local phenomena EPR and GHZ [35], confirmed by solid experimental evidence [36-39].

In Chiatti's and Licata's approach, the two extreme events of a transaction correspond to two reductions of the two state vectors which describe the evolution of the quantum process in the two directions of time. They are also called "**R** processes" (where **R** stands for *reduction*) and here are the only real physical processes. They are constituted of interaction vertices in which real elementary particles are created or destroyed; these interactions are not necessarily acts of preparation or detection of a quantum state in a measurement process. Both the probability amplitudes in the two directions of time and the time evolution operators which act on them are mathematical entities whose only purpose is to describe the causal connection between the extreme events of the transaction, i.e. between **R** processes. This connection is possible because the two events derive from the transformation of the same aspatial and atemporal "substratum". According to this approach, therefore, the history of the Universe and thus the behaviour of matter, considered at the basic level, are interpreted as a complete network of past, present and future **R** processes deriving from the same invariant atemporal substratum. It looks as if every quantum process regarding subatomic particles (as well as time itself) emerge from this invariant atemporal substratum and re-absorbed within it.

In Chiatti's and Licata's approach, this substratum which rules the actual behaviour of matter can also be called "archaic vacuum" to distinguish it from the quantum field theory traditional dynamic vacuum and to indicate all the self-consistency logical constraints which rule "the fabric of reality". In this atemporal substratum, at a fundamental level only the transactions between field modes take place, and the quantum-mechanical wave-function simply emerges as a statistical coverage of a great amount of elementary transitions. This atemporal vacuum generates and conveys the dynamical processes regarding subatomic particles we observe in our measurements. It is a fabric from which patterns emerge by **R** processes and such patterns influence the vacuum activity, in a quantum feedback. Moreover, Chiatti's and Licata's view of transactions emerging from an atemporal "archaic vacuum" leads, from the cosmological point of view, to define an Archaic Universe where the starting point is the group approach to the DeSitter Universe as quantum vacuum's geometrical shape where the old Big Bang conception as a "thermodynamic balloon" seems to be irreparably compromised [32, 33]. In this regard, Licata clearly underlines: "The elimination of the initial singularity by the adoption of de Sitter

5 hyper-sphere as pre-space makes possible a very concise description of the boundary conditions necessary for the evolution of the observed physical universe. Such "archaic pre-space" has not to be considered as antecedent to "Big-Bang", but rather as a pre-spatial and a-temporal substrate of the usual spacetime metric containing *in nuce* all the evolutionary possibilities that the General Projective Relativity equations indicate. After eliminating any geometrical singularity with Euclidean substrate, the description of the Universe evolution can be seen as an extended nucleation from a coherent timeless state (de Sitter isotropic singularity) with very high non-local information to an observable mix of local matter-energy." [31].

4 From Transactions . . . to a Three-dimensional Timeless Non-local Quantum Vacuum

If the quantum behaviour derives from transactional processes defining an archaic, atemporal vacuum and if, in the light of contemporary quantum field theories, the unified quantum vacuum, as a fundamental medium subtending the observable forms of matter, energy and space-time, exhibits zero-point fluctuations which give rise to an enormous vacuum energy density, what can the archaic vacuum energy density be described? And, in synthesis, what is the real, actual, physical link and the interrelation between archaic vacuum, vacuum energy density and non-locality?

As regards the quantum vacuum energy density which should originate the macroscopic space-time, the Planck energy density

$$\rho_{pE} = \sqrt{\frac{c^{14}}{\hbar^2 G^4}} \approx 4,641266 \cdot 10^{113} J/m^3 \cong 10^{97} Kg/m^3 \tag{4}$$

is usually considered as the origin of the dark energy, if the dark energy is supposed to be owed to an interplay between quantum mechanics and gravity. However the observations are compatible with a dark energy given by relation

$$\rho_{DE} \cong 10^{-26} Kg/m^3, \tag{5}$$

thus giving rise to the so-called "cosmological constant problem" because the dark energy (5) is 123 orders of magnitude larger than (4). In order to solve this problem, Santos proposed an interesting explanation for the actual value (5) of the dark energy in which the fluctuations of the quantum vacuum determine a curvature of space and made a calculation, involving plausible hypotheses within quantized gravity, which establishes a relation between the two-point correlation of the vacuum fluctuations

$$C\left(|\vec{r}_1 - \vec{r}_2|\right) = \frac{1}{2} \langle vac| \, \hat{\rho}\left(\vec{r}_1, t\right) \hat{\rho}\left(\vec{r}_2, t\right) + \hat{\rho}\left(\vec{r}_2, t\right) \hat{\rho}\left(\vec{r}_1, t\right) |\rangle \tag{6}$$

and the space curvature [40, 41]. In Santos' approach the dark energy ρ_{DE} is the effect of the quantum vacuum fluctuations on the curvature of space-time according to equation

$$\rho_{DE} \cong 70G \int_0^\infty C\left(s\right) s ds \tag{7}$$

where $C(s)$ is a two-point correlation function of vacuum density fluctuations. Santos' model of quantized general relativity predicts that the quantum vacuum fluctuations actually give rise to a curvature of space-time similar to the curvature produced by a "dark energy" density. The relations between the metric coefficients and the matter stress-energy tensor are non-linear and, as a consequence, the expectation of the metric turns out to be not the same as the metric of the expectation of the matter tensor and the difference between these two quantities gives rise to a contribution of the vacuum fluctuations mimicking the effect of Einstein's cosmological constant. Santos' formalism implies furthermore that the action of the quantum vacuum fluctuations is direct, in the sense that it is expressed by a two-point correlation function that, in the case of equal times, depends only on the distance between those two points.

In the recent paper *Space-time curvature of general relativity and energy density of a three-dimensional quantum vacuum* [42], by following the philosophy that is at the basis of Haisch's and Rueda's model [7], Puthoff's model [8], Consoli's approach [9] and Santos' approach [40, 41], the author of this paper and Sorli have introduced a model of a 3D quantum vacuum in which general relativity emerges as the hydrodynamic limit of an underlying theory of a more fundamental microscopic 3D quantum vacuum condensate. In this approach, the fluctuations of the quantum vacuum energy density generate a curvature of space-time similar to the curvature produced by a "dark energy" density and produce a shadowing of the gravitational space which determines the motion of other material objects present in the region under consideration. Although this approach is in its germinal stages of development, it suggests the relevant perspective to interpret the curvature of space-time characteristic of general relativity as a mathematical value of a more fundamental actual energy density of quantum vacuum which has a concrete physical meaning.

In this model, by starting from the Planckian metric one shows that the fundamental arena of the universe is a 3D isotropic quantum vacuum composed by elementary packets of energy having the size of Planck volume and whose most universal property is the energy density. Here, the ordinary space-time we perceive derives from this 3D isotropic quantum vacuum and this quantum vacuum is assumed to be characterized by processes analogous to Chiatti's and Licata's transactions. In the free space, in the absence of matter, the energy density of the 3D quantum vacuum is at its maximum and is given by the Planck energy density

$$\rho_{pE} = \frac{m_p \cdot c^2}{l_p^3} = \frac{2,1767 \cdot 10^{-8} \cdot (3 \cdot 10^8)^2}{(1,6161 \cdot 10^{-35})^3} = \frac{19,5903 \cdot 10^8}{4,220896 \cdot 10^{-105}} = 4,641266 \cdot 10^{113} \frac{Kg}{ms^2}. \tag{8}$$

In the ordinary space-time we perceive, the appearance of matter endowed with a given mass m corresponds to a more fundamental diminishing of the quantum vacuum energy density. The energy density of quantum vacuum at the centre of this object is given by relation:

$$\rho_{qvE} = \rho_{pE} - \frac{m \cdot c^2}{V} \tag{9}$$

where V is the volume of the massive object under consideration. The appearance of a massive particle in a given region of the ordinary space-time derives from an opportune change of the quantum vacuum energy density $\Delta\rho_{qvE} = \rho_{qvE} - \rho_{pE}$ on the basis of equation

$$m = \frac{V\Delta\rho_{qvE}}{c^2}. \tag{10}$$

Taking account of Santos' results, in our approach the quantized metric of the 3D quantum vacuum condensate is

$$d\hat{s}^2 = \hat{g}_{\mu\nu}dx^\mu dx^\nu \tag{11}$$

whose coefficients (in polar coordinates) are defined by equations

$$\hat{g}_{00} = -1+\hat{h}_{00}, \quad \hat{g}_{11} = 1+\hat{h}_{11}, \quad \hat{g}_{11} = 1+\hat{h}_{11}, \quad \hat{g}_{33} = r^2\sin^2\vartheta\left(1+\hat{h}_{33}\right), \quad \hat{g}_{\mu\nu} = \hat{h}_{\mu\nu} \text{ for } \mu \neq \nu \tag{12}$$

where multiplication of every term times the unit operator is implicit and, at the order $O\left(r^2\right)$, one has

$$\left\langle \hat{h}_{\mu\nu} \right\rangle = 0 \text{ except } \quad \left\langle \hat{h}_{00} \right\rangle = \frac{8\pi G}{3}\left(\frac{\Delta\rho_{qvE}}{c^2} + \frac{35Gc^2}{2\pi\hbar^4 V}\left(\frac{V}{c^2}\Delta\rho^{DE}_{qvE}\right)^6\right)r^2$$

$$\text{and} \quad \left\langle \hat{h}_{11} \right\rangle = \frac{8\pi G}{3}\left(-\frac{\Delta\rho_{qvE}}{2c^2} + \frac{35Gc^2}{2\pi\hbar^4 V}\left(\frac{V}{c^2}\Delta\rho^{DE}_{qvE}\right)^6\right)r^2. \tag{13}$$

In equations (13), $\Delta\rho^{DE}_{qvE}$ are opportune fluctuations of the quantum vacuum energy density which determine the dark energy density on the basis of relation

$$\rho_{DE} \cong 70\frac{G}{4\pi}\left(\frac{V}{c^2}\Delta\rho^{DE}_{qvE}\right)^2 \frac{1}{l}\cdot\frac{1}{l^3} \tag{14}$$

where

$$l = \frac{\hbar}{\left(\frac{V}{c^2}\Delta\rho^{DE}_{qvE}\right)c}. \tag{15}$$

The quantized metric (11) is associated with an underlying microscopic geometry expressed by equations

$$\Delta x \geq \frac{\hbar}{2\Delta p} + \frac{\Delta p}{2\hbar}\left(2\pi^2/3\right)^{2/3} l^{2/3} l_P^{4/3}, \tag{16}$$

which is the uncertainty in the measure of the position,

$$\Delta t \geq \frac{\hbar}{2\Delta E} + \frac{\Delta E T_0^2}{2\hbar}, \tag{17}$$

which is the time uncertainty and

$$\Delta L \cong \frac{\left(2\pi^2/3\right)^{1/3} l^{1/3} l_p^{2/3} T_0 E}{2\hbar} \tag{18}$$

which indicates in what sense the curvature of a region of size L can be related to the presence of energy and momentum in it. Equations (16)-(18) are derived from the quantum uncertainty principle [43] and from the hypotheses of space-time discreteness at the Planck scale by following Ng's treatment [44-47] in which the structure of the space-time foam can be inferred from the accuracy in the measurement of a distance l – in a spherical geometry over the amount of time $T = 2l/c$ it takes light to cross the volume – given by

$$\delta l \geq \left(2\pi^2/3\right)^{1/3} l^{1/3} l_P^{2/3}. \tag{19}$$

The quantized metric (11) allows the quantum Einstein equations

$$\hat{G}_{\mu\nu} = \frac{8\pi G}{c^4}\hat{T}_{\mu\nu} \tag{20}$$

where the quantum Einstein tensor operator $\hat{G}_{\mu\nu}$ is expressed in terms in terms of the operators $\hat{h}_{\mu\nu}$ to be obtained directly: this means that the curvature of space-time characteristic of general relativity may be considered as a mathematical value which emerges from the quantized metric (11) and thus from fluctuations of the quantum vacuum energy density (on the basis of equations (12) and (13)) [42].

Now, the fundamental point of our approach, which allows us to open a connection with the ideas illustrated in the previous chapters, lies in the fact that the quantized metric (11) of the 3D quantum vacuum condensate (whose coefficients are directly associated with the fluctuations of the quantum vacuum energy density on the basis of equations (12) and (13)) is strictly tied to the quantum behaviour of subatomic particles deriving from transactional processes. In this regard, on the basis of the results obtained in the recent paper *Perspectives about quantum mechanics in a model of a three-dimensional quantum vacuum where time is a mathematical dimension* [48], in our model, in analogy with Chiatti's and Licata's approach, the elementary fluctuations of the quantum vacuum energy density physically correspond to the events of preparation of the initial state (creation of a particle or object from the 3D quantum vacuum) and of detection of the final state (annihilation or destruction of a particle or object from the 3D quantum vacuum). The creation and annihilation of an elementary quantum are the two only primary extreme physical events of the 3D quantum vacuum and each corresponds to a peculiar reduction of a state vector (which is constituted of interaction vertices in which real elementary particles are created or destroyed). They can be also called "**RS** processes" where **RS** stands for *state reduction*. These two quantum events of reduction, these two **RS** processes correspond, in our level of physical reality, to the evolution of the quantum process in the two directions of time (namely forward-time evolution and time-reversed evolution respectively, which can be associated with the opportune time evolution operators S and S^+ respectively of the Chiatti-Licata model).

Moreover, one can say that the behaviour and evolution of a particle or object – which is originated by fluctuations of the 3D quantum vacuum energy density – is determined by appropriate waves of the vacuum associated with the wave function which describes the amplitude of creation or destruction events associated with the corresponding fluctuations of the quantum vacuum energy density. The waves of the vacuum act in a non-local way through an appropriate quantum potential of the vacuum (which, so to speak, guides the occurring of the processes of creation or annihilation in the 3D quantum vacuum). The quantum potential of the vacuum can be seen as the primary mathematical reality which emerges from the very real extreme primary physical realities, namely from the processes of creation and annihilation of elementary quanta. In virtue of the primary physical reality of the processes of creation and annihilation and of the non-local action of the quantum potential which is associated with the amplitudes of them, in the 3D quantum vacuum the duration of the processes from the creation of a particle or object till its annihilation has not a primary physical reality but exists only in the sense of numerical order. In other words, the 3D quantum vacuum, as a fundamental medium subtending the observable forms of matter, energy and space-time, is a timeless background: time exists merely as a mathematical parameter measuring the dynamics of a particle or object.

Each **RS** process is a self-connection of the timeless 3D quantum vacuum. A **RS** process that begins with the creation of quality $q$and ends with the destruction of quality $r$can be represented simply by the form q^+r^- and can be described as the concurrence of two distinct transformations. In the first transformation, the 3D quantum vacuum divides into two pairs of opposites: $q+$, q- and $r+$, r- ; the first pair forms "event A", the second pair forms "event B". More precisely, we have an infinite set of loops of self-connections of the event A and an infinite set of loops of self-connections of the event B. The second transformation is the real generation of the transaction having the events $A$and Bas its extremities. It consists in the breaking of Nloops of the first group and Mloops of the second group.

The probability of the occurrence of a creation/destruction event for a quantum particle $Q$of mass (10) in a point event $x$is linked with the probability amplitudes $\psi_{Q,i}(x)$ (for creation events) and $\varphi_{Q,i}(x)$ (for destruction events) of a spinor $C = \begin{pmatrix} \psi_{Q,i} \\ \varphi_{Q,i} \end{pmatrix}$ at two components. The generic spinor $C = \begin{pmatrix} \psi_{Q,i} \\ \varphi_{Q,i} \end{pmatrix}$ satisfies a time-symmetric extension of Klein-Gordon quantum relativistic equation of the form

$$\begin{pmatrix} H & 0 \\ 0 & -H \end{pmatrix} C = 0 \tag{21}$$

where $H = (-\hbar^2\partial^\mu\partial_\mu + m^2c^2)$. Equation (21) corresponds to the following equations

$$\left(-\hbar^2\partial^\mu\partial_\mu + m^2c^2\right)\psi_{Q,i}(x) = 0 \text{ for creation events} \tag{22}$$

$$\left(\hbar^2\partial^\mu\partial_\mu - m^2c^2\right)\varphi_{Q,i}(x) = 0 \text{ for destruction events} \tag{23}$$

which can also be conveniently written as

$$\left(-\hbar^2\partial^\mu\partial_\mu + \frac{V^2}{c^2}\left(\Delta\rho_{qvE}\right)^2\right)\psi_{Q,i}(x) = 0 \text{ for creation events} \tag{24}$$

$$\left(\hbar^2\partial^\mu\partial_\mu - \frac{V^2}{c^2}\left(\Delta\rho_{qvE}\right)^2\right)\varphi_{Q,i}\left(x\right) = 0 \text{ for destruction events} \tag{25}$$

respectively, where $m = \frac{V\Delta\rho_{qvE}}{c^2}$is the mass of the quantum particle under consideration. At the non-relativistic limit, equation (21) becomes a pair of Schrödinger equations:

$$-\frac{\hbar^2}{2m}\nabla^2\psi_{Q,i}\left(x\right) = i\hbar\frac{\partial}{\partial t}\psi_{Q,i}\left(x\right) \text{ for creation events} \tag{26}$$

$$-\frac{\hbar^2}{2m}\nabla^2\varphi_{Q,i}\left(x\right) = -i\hbar\frac{\partial}{\partial t}\varphi^*_{Q,i}\left(x\right) \text{ for destruction events,} \tag{27}$$

which read respectively

$$-\frac{\hbar^2c^2}{2V\Delta\rho_{qvE}}\nabla^2\psi_{Q,i}\left(x\right) = i\hbar\frac{\partial}{\partial t}\psi_{Q,i}\left(x\right) \tag{28}$$

$$-\frac{\hbar^2c^2}{2V\Delta\rho_{qvE}}\nabla^2\varphi_{Q,i}\left(x\right) = i\hbar\frac{\partial}{\partial t}\varphi^*_{Q,i}\left(x\right). \tag{29}$$

The creation of a quantum particle Q of mass (10) is associated with the initial condition for $\psi_{Q,i}\left(x\right)$ in the equation (28), which has only retarded solutions, which classically corresponds to a material point with impulse $\mathbf{p}$ and kinetic energy E $= \mathbf{p}\bullet\mathbf{p}/2m>0$; the destruction of the quantum particle $Q$is associated with the "initial", actually the final, condition for $\psi^*_{Q,i}\left(x\right)$ in equation (29), which has only advanced solutions, which correspond to a material point with kinetic energy E=-$\mathbf{p}\bullet\mathbf{p}/2m<0$. In general, however, the two conditions are different and therefore generate different solutions for the two equations, which are not necessarily mutual complex conjugates.

The non-locality of the 3D quantum vacuum is associated with a quantum potential of the 3D quantum vacuum which can be introduced as the fundamental mathematical element which guides the occurring of the processes of creation and annihilation of quanta in the different regions of the 3D quantum vacuum. In this regard, by writing the two components of the spinor in polar form

$$\psi_{Q,i} = \left|\psi_{Q,i}\right|\exp\left(\frac{iS^\psi_{Q,i}}{\hbar}\right), \tag{30}$$

$$\varphi_{Q,i} = \left|\varphi_{Q,i}\right|\exp\left(\frac{iS^\varphi_{Q,i}}{\hbar}\right) \tag{31}$$

and decomposing the real and imaginary parts of the Klein-Gordon equation (21), for the real part one obtains a couple of quantum Hamilton-Jacobi equations that, by imposing the requirement that they are Poincarè invariant and have the correct non-relativistic limit, assume the following form

$$\partial_\mu\begin{pmatrix} S^\psi_{Q,i} \\ S^\varphi_{Q,i}\end{pmatrix}\partial^\mu\begin{pmatrix} S^\psi_{Q,i} \\ S^\varphi_{Q,i}\end{pmatrix} = \frac{V^2}{c^2}\left(\Delta\rho_{qvE}\right)^2\exp\begin{pmatrix} Q^\psi_{Q,i} \\ -Q^\varphi_{Q,i}\end{pmatrix}, \tag{32}$$

while the imaginary part gives the continuity equation

$$\partial_\mu \left(\rho \partial^\mu \begin{pmatrix} S_{Q,i}^{\psi} \\ S_{Q,i}^{\varphi} \end{pmatrix} \right) = 0 \tag{33}$$

where ρ is the ensemble of particles associated with the spinor under consideration and

$$Q_{Q,i} = \frac{\hbar^2 c^2}{V^2 \left(\Delta\rho_{qvE}\right)^2} \begin{pmatrix} \frac{\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\left|\psi_{Q,i}\right|}{\left|\psi_{Q,i}\right|} \\ -\frac{\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\left|\varphi_{Q,i}\right|}{\left|\varphi_{Q,i}\right|} \end{pmatrix} \tag{34}$$

is the quantum potential of the vacuum. In the non-relativistic limit, equation (32) becomes

$$\frac{c^2}{2V\left(\Delta\rho_{qvE}\right)} \begin{pmatrix} \left|\nabla S_{Q,i}^{\psi}\right|^2 \\ \left|\nabla S_{Q,i}^{\varphi}\right|^2 \end{pmatrix} + Q_{Q,i} + \begin{pmatrix} V \\ -V \end{pmatrix} = -\frac{\partial}{\partial t} \begin{pmatrix} S_{Q,i}^{\psi} \\ S_{Q,i}^{\varphi} \end{pmatrix} \tag{35}$$

and equation (33) becomes

$$\frac{\partial}{\partial t} \begin{pmatrix} \left|\psi_{Q,i}\right|^2 \\ \left|\varphi_{Q,i}\right|^2 \end{pmatrix} + \nabla \cdot \begin{pmatrix} \frac{\left|\psi_{Q,i}\right|^2 \nabla S_{Q,i}^{\psi}}{m} \\ \frac{\left|\varphi_{Q,i}\right|^2 \nabla S_{Q,i}^{\varphi}}{m} \end{pmatrix} = 0 \tag{36}$$

where

$$Q_{Q,i} = -\frac{\hbar^2 c}{2V\left(\Delta\rho_{qvE}\right)} \begin{pmatrix} \frac{\nabla^2\left|\psi_{Q,i}\right|}{\left|\psi_{Q,i}\right|} \\ \frac{\nabla^2\left|\varphi_{Q,i}\right|}{\left|\varphi_{Q,i}\right|} \end{pmatrix} \tag{37}$$

is the non-relativistic quantum potential of the vacuum.

On the basis of equations (34) and (37), both in the relativistic domain and in the non-relativistic domain, both for the processes of creation and for the processes of annihilation, the quantum potential has a non-local, instantaneous action. In other words, the quantum potential of the vacuum guides the occurring of the processes of creation and annihilation of quanta in the different regions of the 3D quantum vacuum in a non-local, instantaneous manner. In sum, the non-local connection between **RS** processes derives from the instantaneous action of the quantum potential guiding the evolution of the occurring of the processes of creation or annihilation of quanta (corresponding to opportune changes of the quantum vacuum energy density) in the different regions of the 3D quantum vacuum. The first component of the quantum potential regards the processes of creation of quanta, the second component regards the processes of annihilation of quanta in the 3D quantum vacuum. Moreover, according to the author, the opposed sign of the second component with respect to the first component translates from the mathematical point of view the idea that, in the 3D quantum vacuum, time exists only as a measuring system of the numerical order of material changes: the sign of the second component indicates that it is not possible to go backwards in the physical time intended as a numerical order [48]. In the light of the action of the quantum potential of the vacuum, according to this approach, the behaviour of the matter in the universe can be seen as an undivided network of **RS** processes that take place in the 3D timeless quantum vacuum. Causal laws are only rules of coherence which must be verified by the network and are *per se* indifferent to the arrow of the time of our level of physical reality.

5 About the Behaviour of the Electron in the Three-dimensional Timeless Non-Local Quantum Vacuum

After seeing how the transactional view leads to the idea of a 3D non-local timeless quantum vacuum characterized by elementary energy fluctuations, we can at this point try to answer to the relevant questions mentioned in the introduction, and to throw thus new light as regards what is the actual behaviour of a subatomic particle. In the model here presented of a 3D timeless non-local quantum vacuum, the evolution of each subatomic particle (such as the electron in a double-slit interference) emerges from opportune elementary **RS** processes of creation/annihilation of quanta. The behaviour of a subatomic particle described by Bohm's approach to quantum mechanics can thus be seen as the result of a more fundamental evolution of fluctuations of the quantum vacuum energy density corresponding to elementary **RS** processes of creation/annihilation of quanta. Moreover, one can say that each elementary **RS** process of creation/annihilation of quanta in the 3D quantum vacuum has indeed a corpuscular and a wave nature. For example, electron can be seen as the result of opportune elementary **RS** processes of creation/annihilation of quanta which can be associated with a opportune waves of the vacuum which evolve according to the general equations (24) and (25) (which become equations (28) and (29) respectively in the non-relativistic limit). Because of its origin from the elementary fluctuations of the quantum vacuum energy density, electron can be therefore associated with appropriate waves of the vacuum which guide it in the different regions of the 3D quantum vacuum through the action of the quantum potential of the vacuum.

In this approach, the behaviour of a quantum particle as we know it from ordinary quantum mechanics actually derives from the equations of the 3D timeless non-local quantum vacuum model. In particular, as regards creation events, in the relativistic domain the fundamental equation of motion is the first of the quantum Hamilton-Jacobi equations (32), namely:

$$\partial_\mu S_{Q,i} \partial^\mu S_{Q,i} = \frac{V^2}{c^2} \left(\Delta\rho_{qvE}\right)^2 \exp Q_{Q,i}, \tag{38}$$

where

$$Q_{Q,i} = \frac{\hbar^2 c^2}{V^2 \left(\Delta\rho_{qvE}\right)^2} \frac{\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)|\psi_{Q,i}|}{|\psi_{Q,i}|} \tag{39}$$

is the quantum potential of the vacuum. In the non-relativistic limit, equation (38) becomes

$$\frac{c\left|\nabla S_{Q,i}\right|^2}{2V\left(\Delta\rho_{qvE}\right)}+Q_{Q,i}+V=-\frac{\partial S_{Q,i}}{\partial t} \tag{40}$$

where

$$Q_{Q,i}=-\frac{\hbar^2 c}{2V\left(\Delta\rho_{qvE}\right)}\frac{\nabla^2\left|\psi_{Q,i}\right|}{\left|\psi_{Q,i}\right|} \tag{41}$$

is the quantum potential of the vacuum. According to equations (38), (39), (40), and (41), the following interpretation of subatomic particles becomes permissible: in our world electrons and other elementary particles have precise positions at every time and follow precise trajectories which emerge from the evolution laws regarding creation events of quanta of the 3D quantum vacuum (38) and (40) and the corresponding quantum potentials (39) and (41) indicate the quantum force exerting on these quanta, which guides the appearance of these quanta in the regions where the wave function of the vacuum is more intense. Therefore, according to the 3D timeless non-local quantum vacuum model here proposed, the quantum potential of ordinary non-relativistic quantum mechanics ($Q=-\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}$ for a one-body system) can be considered a consequence of the more fundamental quantum potential of the quantum vacuum (41) (and an analogous result regards the quantum potential of Klein-Gordon's relativistic quantum mechanics which derives from the more fundamental quantum potential of the 3D quantum vacuum (39)).

As regards the quantum potential of the 3D quantum vacuum ((39) or (41)), it is also important to emphasize that it must not be considered as an external entity in the vacuum but as an entity which contains a spatial information, namely as an entity which expressed the geometrical properties of the 3D quantum vacuum. In other words, this quantum potential can be considered a geometric entity of the vacuum, the information determined by the quantum potential ((39) or (41)) is a type of geometrodynamic information "woven" into the quantum vacuum. The quantum potential of the quantum vacuum has a geometric nature just because has a contextual nature, contains a global information on the environment in which the experiment (deriving from opportune **RS** processes of creation or destruction of opportune qualities) is performed; and at the same time it is a dynamical entity just because its information about the **RS** processes and their environment is active, determines the behaviour of the quantum particles (created or destroyed in the **RS** processes). On the basis of its mathematical expressions, the action of the quantum potential of the vacuum is like-space, namely creates onto the particles (created or destroyed in the **RS** processes) a non-local, instantaneous action. In a double-slit experiment, for example, if one of the two slits is closed the quantum potential of the vacuum changes, and this information arrives instantaneously to the particle, which behaves as a consequence. This means that, at a fundamental level, the 3D timeless non-local quantum vacuum, through its special state represented by the quantum potential of the vacuum, acts as an immediate information medium in determining the motion of a subatomic particle [49].

6 Perspectives about Quantum Behaviour of Matter and Gravity as Two Different Aspects of the Three-dimensional Timeless Non-Local Quantum Vacuum

Besides the possibility to obtain a complete derivation of the quantum formalism and an interesting reading of the quantum dynamics as a particular aspect of such general theory, another relevant merit of this approach lies in a suggestive interpretation of gravity as a phenomenon emerging from the 3D timeless non-local quantum vacuum. The 3D timeless non-local quantum vacuum model introduces the interesting perspective to interpret gravity and quantum behaviour as two different aspects of a same source, of a same coin.

In this regard, A. Shojai and F. Shojai recently developed an interesting toy model which, studying the behaviour of spinless particles in a curved space-time, demonstrates that the quantum potential provides an additional contribution to the curvature that is added to the classic one and that reveals deep and unexpected connections between gravity and the quantum phenomena [50, 51]. By the investigation of the coupling of purely gravitational effects and purely quantum effects of a particle in a general background space-time metric, this approach can obtain a fundamental equivalence of quantum effects of matter and a curved space-time. By the analysis of the quantum effects of matter in the framework of bohmian mechanics, A. Shojai's and F. Shojai's model shows that the motion of a spinless particle with quantum effects is equivalent to its motion in a curved space-time. The quantum effects of matter as well as the gravitational effects of matter have geometrical nature and are highly related: the quantum potential can be interpreted as the conformal degree of freedom of the space–time metric and its presence is equivalent to the curved space-time. In fact, the presence of the quantum force is just like having a curved space–time which is conformally flat and the conformal factor is expressed in terms of the quantum potential. All this is expressed by an equation of motion of the form

$$\tilde{g}^{\mu\nu}\tilde{\nabla}_\mu S\tilde{\nabla}_\nu S = m^2c^2 \tag{42}$$

where S is the phase of the wave function ψ, $\tilde{\nabla}_\mu$ is the covariant differentiation with respect to the metric

$$\tilde{g}_{\mu\nu} = \frac{M^2}{m^2}g_{\mu\nu} \tag{43}$$

(which is a conformal metric) where the quantum mass is

$$M^2 = m^2 \exp Q, \tag{44}$$

where

$$Q = \frac{\hbar^2}{m^2c^2}\frac{\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)_g |\psi|}{|\psi|} \tag{45}$$

is the quantum potential. The important conclusion of F. Shojai's and A. Shojai's model is that the presence of the quantum potential is equivalent to a curved space-time with its metric being given by (45), providing thus a fundamental geometrization of the quantum aspects of matter.

Here, in analogy to the conclusions of F. Shojai's and A. Shojai's model, we can show that, in our model of a 3D timeless non-local quantum vacuum characterized by **RS** processes, quantum behaviour of matter and gravity constitute two different aspects deriving from the same 3D timeless non-local quantum vacuum. In this regard, by starting from Bohm's version of Klein-Gordon equation of the generic component of the probability amplitude of the occurrence of creation event for a quantum particle Q based on equations (38) and (39), one can show that the generic component of the spinor associated with the quantum particle under consideration (and thus the quantum potential associated with it) has an important link with the curvature of the ordinary space-time we perceive. This means that the effects of gravity on geometry and the quantum effects on the geometry of space-time are highly coupled and that both of them derive from the **RS** processes of the 3D timeless non-local quantum vacuum.

By starting from equation (38), the extension to the case of a particle moving in a curved background can be done by changing the ordinary differentiating ∂_μ with the covariant derivative ∇_μ and by changing the Lorentz metric with the curved metric $g_{\mu\nu}$. In this way, we obtain the equations of motion for a change of the quantum vacuum energy density (which determines the occurrence of creation event for a quantum particle Q of mass (10)) in a curved background:

$$\tilde{g}_{\mu\nu}\tilde{\nabla}_\mu S_{Q,i}\tilde{\nabla}_\nu S_{Q,i} = \frac{V^2\left(\Delta\rho_{qvE}\right)^2}{c^2\hbar^2}, \tag{46}$$

where $\tilde{\nabla}_\mu$ represents the covariant differentiation with respect to the metric

$$\tilde{g}_{\mu\nu} = g_{\mu\nu}/\exp Q \tag{47}$$

which is a conformal metric, where

$$Q_{Q,i} = \frac{\hbar^2 c^2}{V^2\left(\Delta\rho_{qvE}\right)^2}\frac{\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)_g |\psi_{Q,i}|}{|\psi_{Q,i}|} \tag{48}$$

is the quantum potential of the vacuum.

The important conclusion we can draw from this treatment is that the presence of the quantum potential of the vacuum is equivalent to a curved space-time with its metric being given by (47). On the ground of equations (44)-(46), it becomes so permissible the following reading, the following interpretation of the curvature of space-time (and thus of gravitation) inside the 3D timeless non-local quantum vacuum characterized by **RS** processes. **RS** processes associated with creation events of quantum particles determine a quantum potential of the vacuum which is equivalent to the curvature of the space-time. The quantum potential of the vacuum corresponding to the generic component of the spinor of a quantum particle is tightly linked with the curvature of the space-time we perceive. In other words, we can say that **RS** processes, through the manifestation of the quantum potential of the vacuum (48), lead to the generation, in our macroscopic level of reality, of a curvature of space-time and, at the same time, the space-time metric is linked with the quantum potential of the vacuum which influences and determines the behaviour of the particles (themselves corresponding to creation events of the 3D timeless non-local quantum vacuum).

In this way, we have achieved the geometrization of the quantum aspects of matter and the source of this geometrization can be considered the 3D timeless non-local quantum vacuum characterized by **RS** processes. In this picture, one can say that the space-time geometry sometimes looks like what we call gravity and sometimes looks like what we understand as quantum behaviours and both these features of physical geometry emerge from the **RS** processes of the 3D timeless non-local quantum vacuum.

7 Conclusions

In order to face the fundamental questions regarding what is the real background of physics, what is the actual meaning of "motion" of a subatomic particle such as, for example, the electron and if between the different descriptive levels of physical reality there are only formal analogies or there is a deeper meaning, we have started from Bohm's quantum physics vision and, by assuming non-locality as the ultimate visiting card of quantum geometry, we have arrived to the idea of a three-dimensional timeless non-local quantum vacuum characterized by elementary processes of creation/annihilation of quanta. Bohm's 1962 words at BBC illustrating that the electron intended as a wave or a corpuscle (satisfying the well known laws of quantum theory) has not a primary physical existence but its "physical appearance" actually emerges from more elementary processes of formation and dissolving, can be considered the real, actual starting-points and epistemological foundations of the idea of a non-local quantum vacuum as fundamental arena of the universe, as ultimate descriptive level of quantum processes. The intrinsic non-locality of Bohm's approach leads to Kastner's transactional interpretation and then to Chiatti's and Licata's transactions as fundamental processes of an archaic vacuum as "fabric of reality". Hence, in order to reproduce the energy density of quantum vacuum the step is brief and the approach of the three-dimensional timeless non-local quantum vacuum characterized by elementary **RS** processes of creation/annihilation of quanta proposed by the author of this paper allows us to "close the circle" and "resolve" the problem introduced by Bohm in his 1962 words at BBC.

In virtue of the ontology which derives from the 3D timeless non-local quantum vacuum model here suggested, we can conclude that the primary physical reality of subatomic processes is constituted by **RS** processes of creation/annihilation of quanta associated with energy fluctuations of the energy density of the 3D timeless non-local quantum vacuum. By using a Bohmian terminology, we can define the reality constituted by the **RS** processes and their evolution through the non-local action of the quantum potential of the vacuum as the background from whose differentiation the foreground constituted by the events of a given subatomic particle or system (governed by the well-known laws of quantum theory) emerges. By attributing the status of primary physical reality solely to the arena of **RS** processes it follows that the spacetime coordinates are labels associated with these processes and which express certain properties of relation between them. Spacetime as such is only the domain setoff this labels and has no physical reality of its own. It is, so to speak, materialized by **RS** processes. In analogous way, also the background associated with the de Broglie-Bohm pilot-wave theory but also of Bohm's implicate order and Hiley's pre-space can be seen as manifolds deriving from this more fundamental arena represented by the three-dimensional non-local timeless quantum vacuum, are someway "materialized" by **RS** processes. The philosophy of this model as regards the link between our level of physical reality (regarding measurement processes), the implicate order and the 3D timeless non-local quantum vacuum actually follows someway the program that Bohm had already sketched out when had studied the relationship between implicate and explicate order and at the same time allows us to go beyond it, suggesting a possible deeper origin and explanation of Bohm's implicate order. In this way, the problem regarding the existence, in quantum physics, of different descriptive levels of physical reality, whether formal analogies exist between them or there is a deeper meaning, gets a new significance. In fact, one can say that, since each subatomic particle (such as the electron in the famous double-slit interference experiment) is indeed the evolution of **RS** processes of creation/annihilation of quanta corresponding to elementary fluctuations of the quantum vacuum energy density, there is an equivalence between the 3D timeless non-local quantum vacuum and the space-time background of the subatomic particle into consideration (and in this sense there is a formal analogy between the 3D timeless non-local quantum vacuum and the usual background of quantum theory), but at the same time the 3D timeless non-local quantum vacuum allows to go beyond suggesting a deeper meaning about the relationships between the different descriptive levels of physical reality. In fact, on one hand, with the introduction of a three-dimensional timeless non-local quantum vacuum defined by **RS** processes of creation/annihilation of quanta corresponding to elementary fluctuations of the quantum vacuum energy density, the ordinary quantum mechanics emerges directly from the three-dimensional timeless non-local quantum vacuum. On the other hand, this approach has the merit to introduce a significant geometrization of physics which arises in the fundamental processes of the three-dimensional timeless non-local quantum vacuum: in virtue of the **RS** processes and the changes of the energy density corresponding to them, the quantum behaviour of matter and gravity appear as two different aspects of this fundamental arena (thus introducing new perspectives of unification between quantum physics and general relativity).

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