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QUANTUM ENTITIES AND THE NATURE OF TIME

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Abstract

The conceptual statute of modern quantum theory was formulated during the 5th Solvay Conference in 1927 and since then accepted as definitive, although criticisms and discussions have continued up to the present. The more properly physical aspects of the debate seem to concern the relationship between quantum entities and spacetime. A historical circumstance that should not be ignored is that in 1927 the exploration of the realm of the fundamental constituents of matter (the so-called "elementary particles") was just in its infancy, and therefore the properties of these constituents could not play a constitutive role in the theory. Here we propose to re-read the nature of quantum entities starting from the peculiar relationship that the elementary particles that constitute them maintain with the spatial domain. In particular, it is assumed that this relationship is mediated by time and that the time accessible to elementary particles (but not to the systems they compose) is a complex variable rather than a real one. This approach helps to dissolve much of the "mystery" surrounding quantum phenomena.

Introduction

After almost thirty years of tumultuous gestation, in October 1927 quantum theory reached its conceptual framework considered definitive. This took place in Brussels, at the 5th International Conference promoted by the Belgian industrialist E. Solvay, which was entirely dedicated to the subject, although many of the concepts exposed had already been presented by Bohr the previous month in Como, on the occasion of the congress held to honor Alessandro Volta [1,2]. It is not our intention here to examine the elements of the "orthodox" interpretation of quantum phenomena proposed on these occasions, nor to retrace the debate on it, which in reality is still going on. Our brief contribution, enclosed in the space of this letter, intends instead to highlight two points.

The first point concerns the state of physical knowledge in 1927. At that time, the research sector that we now call "elementary particle physics" was, one can say, in its infancy. The only known particles were the electron, discovered by J.J. Thomson in 1897, and the proton discovered by E. Rutherford in 1917 (although previously known in chemistry as ionized hydrogen). To this list, we must add the photon, postulated by Einstein in 1905 to explain the photoelectric effect, and the existence of which had only recently been definitively accepted by the physics community. Nothing more. Even just to complete the picture of the particulate constitution of ordinary matter, the neutron was missing (which will be discovered by J. Chadwick in 1932). This constitution could therefore not play any founding role in the conceptual framework of the theory. On the contrary, the new quantum theory was seen and used as a convenient formalism for deciphering this constitution on the various microphysical scales: molecules, atoms, nuclei, and particles; and this approach remains to this day.

The second point concerns the peculiar relationship between quantum entities and space. Quantum entities are frequently "delocalized" in space, and this delocalization cannot be explained in terms of mere ignorance of their actual location. It seems to us that a relevant part of the debate on the foundations of quantum theory, if not the entire debate, can be traced back to the need to clarify this relationship. We assume here that the mechanism underlying this peculiar relationship between matter and space is operative at the level of the elementary particles of matter, and that at the level of composite systems, it is normally hidden by the internal decoherence of these systems. We attribute to the elementary particles not only the role of ultimate constituents of matter in a spatial sense (*i.e.*, of elementary bricks derivable from a hypothetical process of subdivision *ad libitum* of a material system performed at a fixed instant) but also, and above all, of ultimate constituents in a temporal sense. That is, we assume that quantum discontinuity (quantum jumps, "collapse" of the state vector) manifests itself precisely as a discontinuous and non-unitary aspect of the *known* interactions between elementary particles. This discontinuity produces the decoherence that leads to classicalization.

In this sense our attention, rather than to the dual nature, wavelike and corpuscular, of the particles, is directed to the dual nature, unitary and non-unitary, of their interactions; with the further clarification that we are referring here to the usual and well-known interactions described by the Standard Model, plus gravitation. From this perspective, the usual reading of quantum theory is reversed: quantum discontinuity (= reduction of the state vector), is no longer an unexpected or unwanted guest. Instead, it becomes a fundamental fact, which identifies a level of physical reality: the one at which discontinuity manifests itself. This level is that of elementary particles and their ordinary interactions, and the existence of this level becomes a constitutive element of the conceptual framework of quantum theory, rather than a mere applicative consequence of the theory itself.

Our goal therefore becomes the reformulation of the relationship between elementary particles and the spatial domain. We assume that this relationship is time-mediated, in the sense that elementary particles, unlike composite systems, have access to a time that is a complex, rather than a real, variable. This assumption makes it possible to accommodate quantum discontinuity as a peculiar aspect of the level of elementary particles, giving substance to the reasoning proposed in the previous paragraphs.

The plan of the exposition is as follows: in Section 1 we present the essential points of the proposal, including the notion of complex time and the connection between this notion and the principles of usual quantum theory. Section 2 specifically examines the question of Einstein's locality, specifying that this important principle of physics remains valid also in the proposed picture; an aspect, this, that greatly concerned Einstein.

In Section 3 a connection is sketched between the deformation of the vacuum described through the complex time and the localization of the charges in the time domain, operated by the interactions. Through this reading of the wave-particle dualism, the scale of the elementary particles is fixed. It is important to underline that the historical root of the hypotheses proposed in this work is to be found in Bohr's early work on radiation phenomena, an aspect that is discussed in Section 4. The differences between this model and the hypothesis of particle-objects embedded in their wave function are discussed in Section 5. Section 6 reports the conclusions.

1. The proposal

Let us consider the well-known de Broglie phase factor [3] of an elementary particle, $\exp(\pm i\varphi)$, where

$$\frac{\varphi\hbar}{Mc^2} = t_{pr} \tag{1}$$

In this relation, M is the particle mass and t_{pr} is its proper time. We introduce a complex time ζ through the relation:

$$\zeta = \rho e^{\pm i\varphi} = R + iI \tag{2}$$

where:

$$\rho = \theta_0 \, e^{-|\tau|/\theta} \tag{3}$$

$$0 \leq \theta \leq \theta_0 \tag{4}$$

Here θ_0 is a universal constant while θ is a particle motion constant; R, I, τ are real numbers and all these quantities are time intervals. The de Broglie phase wave then corresponds to the circumference of radius $\rho = \theta_0$ on the complex plane (R, I). From (1) it is immediately evident that the propagation interval of the de Broglie phase between two successive quantum jumps which occur respectively at instants t_1 and $t_2 > t_1$ of proper time corresponds to an interval of the variable φ. This interval in turn corresponds, by (2), to an arc on the circumference $\rho = \theta_0$ (possibly more extended than the circumference itself, which is retraced in this case). The endpoints A, B of this arc are connected to the center O of the circumference by the radii OA, OB respectively. These radii are expressed by (3) with the position that for the radius OA, corresponding to the value t_1 of the proper time, τ varies from $-\infty$ to 0; for the radius OB, corresponding to the value t_2 of the proper time, τ varies instead from 0 to $+\infty$. The radius OA therefore comes to correspond to the quantum jump which *initiates* the propagation of the arc AB; the radius OB instead corresponds to the quantum jump that *ends* this propagation (Fig. 1).

What has been said corresponds to the following pair of statements: 1) quantum jumps can be treated on the same foot as the unitary propagation of the quantum amplitude if one admits that time is a complex variable; 2) since all the quantum jumps that the particle undergoes are connections between the time domain t_{pr}, represented by the circumference, and the center O of the circumference itself, then O "sees" this domain as a whole, a sort of eternal present. One can express the same concept in another way by saying that from the perspective of t_{pr}, O is "timeless".

Let us now examine in more detail the implications of statement 2). The interval ($t_2 - t_1$) can be subdivided into n_t identical contiguous intervals, whose length δ will tend to zero as n_t tends to infinity. From Dirac's theory of spin ½ fermions, we know that in this limit the velocities $c\boldsymbol{\alpha}_k$ ($k = x$, y, z) have eigenvalues $\pm c$. In other words, the elementary intervals into which we have divided the original interval ($t_2 - t_1$) are jumps at the speed of light c in one of the three directions of space: x or y or z. Therefore, indicating with the relative integer n_k the difference between the number of jumps made along the coordinate k in the direction of the increasing coordinate and the number of jumps made in the opposite direction, we easily obtain that:

$$n_t \geq |n_x| + |n_y| + |n_z| \tag{5}$$

That is:

$$(n_t)^2 \geq \left(|n_x| + |n_y| + |n_z|\right)^2 \geq |n_x|^2 + |n_y|^2 + |n_z|^2 \tag{6}$$

Observing that $n_t = (t_2 - t_1)/\delta$ and that $|n_k|(c\delta)$ is the modulus of the interval along the direction k covered by the sequence of jumps considered, equation (6) can be transformed into a relation between intervals:

$$c^2(t_2 - t_1)^2 \geq (x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2 \tag{7}$$

Eq. (6) can also be easily obtained by expressing the Eq. (5) directly in terms of Dirac operators $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$:

$$c(t_2 - t_1)\,\boldsymbol{\beta} \geq (x_2 - x_1)\boldsymbol{\alpha}_1 + (y_2 - y_1)\boldsymbol{\alpha}_2 + (z_2 - z_1)\boldsymbol{\alpha}_3 \tag{8}$$

By squaring (8) twice and adding the expressions obtained, from the anticommutation rules of Dirac's operators we get again (7). Equation (6) expresses the belonging of the sequence of jumps to a single light cone on the Minkowskian spacetime and therefore the fact that this sequence is causal. Naturally, for the same value of n_t there may be different values of (n_x, n_y, n_z) and therefore different values of the final spatial point on the hyperplane $t_{pr} = t_2$, or of the initial spatial point on the hyperplane $t_{pr} = t_1$. In other words, the particle is "diffused" or "delocalized" over all space at every instant.

This means, on the other hand, that the center O of the circumference "sees", through the quantum jump represented by the radius OB, *all* the points of the three-dimensional space $t_{pr} = t_2$ and, through the quantum jump represented by the radius OA, *all* the points of the three-dimensional space $t_{pr} = t_1$. Therefore, instead of speaking of spatial delocalization of the particle, we can equivalently state that, from the perspective of three-dimensional space, O is "aspatial".

It is possible to transform the coordinates in order to preserve causality and therefore Equation (7). The Lorentz-Poincaré transformations thus obtained, as is known, change (t_{pr}, 0, 0, 0) into (t, x, y, z). The consequence is that the de Broglie phase factor becomes a plane wave: $\exp(iMc^2 t_{pr}/\hbar) \rightarrow \phi =$

$\exp(i\boldsymbol{p}\bullet\boldsymbol{x}/\hbar - iEt/\hbar)$, where $\boldsymbol{p}$ is the momentum of the particle and E its energy [3]; these quantities satisfy the relativistic dispersion relation with a mass value equal to M:

$$E^2 = \boldsymbol{p}^2c^2 + M^2c^4 \tag{9}$$

Therefore ($\Box$ is the D'Alembert operator):

$$(\hbar^2\Box + M^2c^4)\phi = 0 \tag{10}$$

Due to the linearity of (10), the space-time part $\psi(\boldsymbol{x}, t)$ of the wave function of the particle (more generally, each component of its spinor wave function) will be a solution of (10):

$$(\hbar^2\Box + M^2c^4)\psi = 0 \tag{11}$$

to the extent that it will be expressible as a superposition of terms ϕ satisfying (10). The causal structure of the wave packet propagation is then encapsulated in the Green's function of (11). However, the complete wave function is, for (2)-(4), $\Gamma\psi$, where $\Gamma = \rho(\tau)/\theta_0$ is the solution of the Schrödinger equation in imaginary time:

$$\hbar^2(\partial^2/\partial\tau^2 + 1/\theta^2)\Gamma = 0 \tag{12}$$

independent of space-time coordinates. The transition from imaginary time $\tau \in (-\infty, 0]$ to real time t at the instant $t = t_{jump}$ in a given reference frame, for $\tau = 0$, is the creation of the new state ψ in a quantum jump at $t = t_{jump}$. The inverse passage, at $t = t_{jump}$, from real time t to imaginary time $\tau \in [0, +\infty)$, again for $\tau = 0$, is the annihilation of the previous state in the same quantum jump. As can be seen, creation and annihilation involve the entire spatial domain at the same instant and can be traced back to a specific Wick rotation. It is therefore easy to convince oneself that the non-local aspects of the wave function manifest themselves only during the quantum jumps, being the unitary propagation completely causal due to (7),(11). The existence of sequences of infinitesimal jumps at the speed of light can be expressed in another way by stating that time t exists in the three variants x, y, z. A difference between the time t counted along the circumference $\rho = \theta_0$ in the plane of complex time and the time ρ counted along the radii of this circumference is that the latter, however, does not exist in these variants. So ρ is aspatial, as is O.

O is therefore the unperturbed state of the vacuum, of which the particle represents a deformation. The reasoning exposed therefore tells us that in its unperturbed condition, the vacuum is aspatial and timeless, therefore something very different from a classical ether diffused *in* space and variable *over* time. The deformations of this vacuum are, however, labeled by the space-time coordinates and correspond to a particle "delocalized" in space.

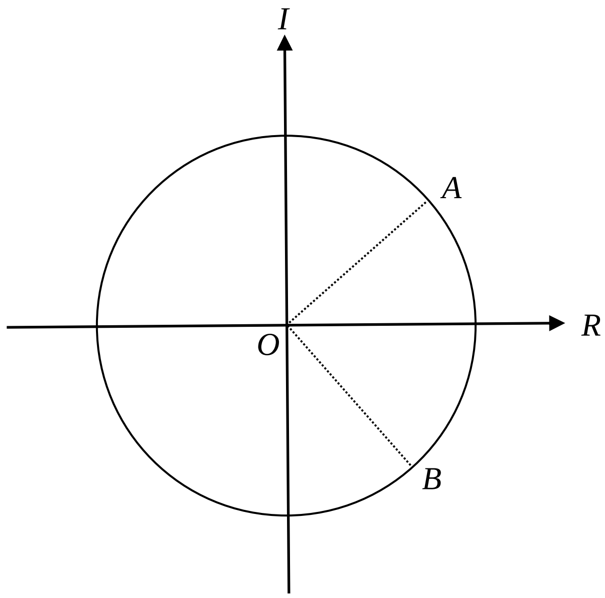

Figure 1. The complex time plane.

2. Einstein locality

The content of the previous Section clarifies that in the quantum jump associated, we say, with the absorption of a particle at point *A* of a screen and the simultaneous cancellation of its wave function at a point *B* distant from *A*, there is no violation of Einstein locality [4]. In fact, *A* and *B* do not exchange any superluminal signal. Simply, the particle wave function $\psi(\mathbf{x}, t)$ is the spatiotemporal part of a larger wave function that must be written as $(\rho(\tau)/\theta_0)\psi(\mathbf{x}, t)$. For the instants t before the jump, $\rho(\tau)/\theta_0 \equiv 1$ and the wave function reduces to the solution $\psi(\mathbf{x}, t)$ of the conventional wave equation (11). At time $t = t_{jump}$ of the jump, τ varies from 0 to $+\infty$, with the result that $(\rho(\tau)/\theta_0)\psi(\mathbf{x}, t) \rightarrow 0$ *for any value* of $\mathbf{x}$. At time instants following t_{jump}, the wave equation (11) has a solution that evolves from a new zero initial condition at $t = t_{jump}$; this solution is obviously null everywhere and always.

Very similar considerations apply to entangled states of several particles, for example, $|\psi_a\rangle_1 |\psi_a\rangle_2 + |\psi_b\rangle_1 |\psi_b\rangle_2$, where ψ_a, ψ_b, are two possible (stationary) states of particles 1 and 2 of mass M_1, M_2 respectively. An interaction detecting particle 1 at time t_1 in the state ψ_a and an interaction detecting particle 2 at time t_2 in the state ψ_a produce the reduction:

$$|\psi_a\rangle_1 |\psi_a\rangle_2 + |\psi_b\rangle_1 |\psi_b\rangle_2 \rightarrow \exp\left(\frac{iM_1c^2(t_2 - t_1)}{\hbar}\right) |\psi_a\rangle_1 |\psi_a\rangle_2 \qquad (13)$$

in a reference where $t_2 > t_1$, and:

$$| \psi_a\rangle_1 \,|\, \psi_a\rangle_2 + |\, \psi_b\rangle_1 \,|\, \psi_b\rangle_2 \rightarrow \exp\left(\frac{iM_2c^2(t_1-t_2)}{\hbar}\right) |\, \psi_a\rangle_1 \,|\, \psi_a\rangle_2 \qquad (14)$$

in a reference where $t_2 < t_1$. By comparing the quantum amplitudes (13) and (14) coming out of the reduction, it can be seen that they differ only by a global phase factor, and therefore represent the same physical state. Again, therefore, there is no violation of Einstein locality caused by the propagation of a superluminal signal between particles 1 and 2. More simply, all the factors $(\rho(\tau)/\theta_0)$ implicit in the total amplitude $(\rho_{1,a}(\tau_{1.a})/\theta_0)$ $(\rho_{2,a}(\tau_{2,a})/\theta_0)$ $|\, \psi_a\rangle_1 \,|\, \psi_a\rangle_2$ + $(\rho_{1,b}(\tau_{1,b})/\theta_0)$ $(\rho_{2,b}(\tau_{2,b})/\theta_0)$ $|\, \psi_b\rangle_1 \,|\, \psi_b\rangle_2$ go to zero in both interactions, while only the factors $(\rho(\tau)/\theta_0)$ implicit in the amplitude $(\rho_{1,a}(\tau_{1,a})/\theta_0)$ $(\rho_{2,a}(\tau_{2,a})/\theta_0)$ $|\, \psi_a\rangle_1 \,|\, \psi_a\rangle_2$ grow back to 1 (that is, $\tau_{1,a}$ and $\tau_{2,a}$ change from $-\infty$ to 0) in both interactions.

In a given reference, one of the two factors $(\rho_{1,b}(\tau_{1,b})/\theta_0)$, $(\rho_{2,b}(\tau_{2,b})/\theta_0)$ vanishes before the other. This determines the cancellation of the entire branch $(\rho_{1,b}(\tau_{1,b})/\theta_0)$ $(\rho_{2,b}(\tau_{2,b})/\theta_0)$ $|\, \psi_b\rangle_1 \,|\, \psi_b\rangle_2$ of the original state vector and, therefore, also of the other factor. The annulment of the two factors therefore proceeds in a coherent manner, albeit differently ordered in different references. This is made possible by the independence of the two factors from the spatiotemporal coordinates that label the interactions. This independence expresses the common emergence of the amplitudes from the timeless and aspatial vacuum O, or their common reabsorption into it.

3. Complex time vs. de Broglie phase

In Section 1 we started from the de Broglie phase factor as the primary fact and built on it to introduce a notion of complex time. We have followed this path because the notion of de Broglie's phase is widespread and shared. However, we note that the reverse path could also have been followed, that is, introducing a notion of complex time and deriving from it the de Broglie phase.

The meaning of the de Broglie phase is that the probability of finding the "particle" at any instant of its proper time t_{PR}, *i.e.*, at a specific angle on the circumference of radius θ_0 in the plane of complex time, does not depend on t_{PR}; that is: it does not depend on the angle. In other words, the particle state is persistent. If we assume that also the interferometric properties of the quantum amplitude of the corpuscle do not depend on its proper time t_{PR}, *i.e.*, if we assume stationarity as well as persistence, then the amplitude can only be of the form $exp(\pm ik\cdot t_{PR})$, where $k\cdot t_{PR}$ is, up to an additive constant, the angle on the circumference. In this case, in fact, the transformation $t_{PR} \rightarrow t_{PR} + t_0$ sends $exp(\pm ik\cdot t_{PR})$ in $exp(\pm ik\cdot t_{PR})*exp(\pm ik\cdot t_0)$, *i.e.*, it leaves the amplitude unchanged except for a phase shift. Obviously, $k = Mc^2/\hbar$, where M is the particle rest mass.

The introduction of a complex time leads us to ask ourselves what the evolution parameter of the vacuum τ could be, and how this parameter can be reconnected to known properties of elementary particles. This is a completely open problem that will not be explored here: proposing a resolution means proposing a specific model of the dynamics of the quantum jump in the evolution parameter τ. We therefore limit ourselves to an extremely rough consideration on θ.

A dynamic in the "hidden" time τ (hidden because it is not connected to the evolution of states entering or leaving the quantum jump, the only ones experimentally accessible) exists only in conjunction with discontinuities associated with the particle's localization in the time domain; that is, contextually to an interaction during which the charge q of the particle, relative to that specific interaction, is localized in time domain t. If we very crudely assimilate the time interval θ to the time constant of a capacitor of capacity C charged to the level q, and we interpret (3) as an expression of the discharge/charge of this capacitor, it is natural to pose [5]:

$$\frac{q^2}{2C} = Mc^2 \tag{15}$$

where M is the rest mass of the particle. From the relation $C = 2\pi\varepsilon_0 r$, which expresses C as a function of a vacuum constant ε_0 and a dimension r of the capacitor, we obtain:

$$r = \frac{q^2}{4\pi\varepsilon_0 Mc^2} \tag{16}$$

If we refer to the charged elementary fermions of the Standard Model (charged quarks and leptons) and interpret q as their electric charge, equation (16) is the expression of their classical radius. Then setting the time constant θ as equal to r/c, we obtain:

$$\theta = \frac{q^2}{4\pi\varepsilon_0 Mc^3} \leq \frac{e^2}{4\pi\varepsilon_0 m_e c^3} = \theta_0 \tag{17}$$

where e is the elementary charge and m_e is the mass of the electron. The particle scale θ_0 is then defined as the time taken by light to travel the electron classical radius. Moreover, from the expression of the θ interval as a time constant, $\theta = RC$, it follows that the resistance R coincides (up to a factor $1/2\pi$) with the ordinary vacuum impedance: $R = \theta/C = \theta/(2\pi\varepsilon_0 c\theta) = (1/2\pi)\,(\mu_0/\varepsilon_0)^{1/2} = 60$ Ohms.

It should be noted that, in (15), q represents the charge localized at the instant t_{jump} of the time domain t, not the charge "carried" by a hypothetical object-particle. If there is no localization of charge in time t, the left side of (15) is therefore null; consequently, the right side is also zero, which represents the energy located in time. Since time and energy located in time are conjugate variables, the duration of the state is then completely indefinite. We thus return to the de Broglie phase factor. The reasoning leading to (17) therefore does not imply any spatially extended distribution of charge of the elementary fermions, but only an inertia of the vacuum to the creation/annihilation of their dynamic states; that is, to the temporal localization of these particles.

4. Historical interlude: the (possible) reasons for a silence

It is known that, historically, the notion of "quantum jump" was introduced by Bohr in his atomic model of 1913 precisely in reference to radiation phenomena, *i.e.*, the interaction between atomic electrons and photons [6]. Bohr was clearly aware of the extra-spatiotemporal aspects involved in quantum jumps. Here are two quotes:

It is my personal opinion that these difficulties [in the atomic theory] are of such a nature that they hardly allow us to hope that we shall be able, within the world of the atom, to carry through a description in space and time that corresponds to our customary sensory images. (Letter to Harald Høffding, September 1922)

It is . . . probable that the chasm appearing between these two different conceptions of the nature of light [corpuscular and wavelike] is an evidence of unavoidable difficulties of giving a detailed description of atomic processes without departing essentially from the causal description in space-time that is characteristic of the classical mechanical description of nature.

These quotes are reported in Darrigol [7], who makes an important point for our purposes:

To avoid a common misinterpretation of the latter statement, I will recall that Bohr's rejection of any space-time description of radiation processes in late 1922 did not concern his previous use of space-time pictures for electronic motion and freely waving electromagnetic fields. In his opinion these pictures remained the necessary basis for the application of the correspondence principle; but their validity was to be limited to the approximation where the interaction between the two entities in question, the radiation field and the electronic orbits, could be neglected; and they were of a purely formal nature, since the "correspondence" between the electronic orbits and the emitted radiation could not be deduced from a causal mechanism occurring in space and time.

One inevitably wonders why Bohr, who had introduced quantum jumps in 1913 and was so acutely aware of the limitations of spatiotemporal description, did not place quantum jumps at the center of his 1927 interpretation.

A possible historical explanation can be offered by his meeting with Schrödinger in Copenhagen in September 1926, at which Heisenberg was also present, after the success of wave mechanics [8]. Schrödinger was convinced that this success justified the elimination of "absurd quantum jumps". The idea defended by the Austrian scholar was that of reducing the wave-particle duality to the wave-like aspect only. Atomic transitions, for example, were reduced to the gradual and continuous evolution of the atomic wave function from the initial condition to the final state, without discontinuous jumps. Bohr was worried that the success achieved by wave mechanics, much more understandable and far more easily usable than the matrix mechanics developed by his student Heisenberg, could obscure the results obtained by the latter. But, apart from this "head boy" concern, Bohr was not convinced that the quantum jumps and the extra-spatiotemporal aspects of interactions, in his opinion so well represented in the matrix formulation, could be dismissed.

The meeting was profitable for all [8]: Schrödinger realized that particles could not be simulated by wave packets, since these generally dispersed. Heisenberg realized that the wave formulation could allow an easier calculation of the transition matrices, the real operational obstacle of the matrix formulation. Everyone understood that in reality they were talking, once the ideological oppositions had been overcome, of the same theory in two different formulations, which could benefit from each other. This suspicion was subsequently confirmed by Schrödinger himself with a well-known equivalence theorem, stimulated by those discussions.

It was starting from that conversation that Bohr began to reflect on the interpretation that he would later make public in the conferences in Como and Brussels in the fall of 1927 [2,8]. His aim was to formulate a hermeneutic of quantum formalism that would highlight the connection between the results of the Copenhagen-Göttingen matrix approach and those of the wave approach, in such a way as to constitute a common justification. As we know, the key proposed by Bohr was complementarity. In a quantum system, both the wave and the corpuscular aspects are present together, at the same instant and in the potential state; it is the choice of the methods of experimental interrogation of the system that determines which of these aspects manifests itself in a decisive way.

This proposal is notoriously problematic. An electron fired from an electron gun towards a photographic plate behaves as a particle only in two separate instants: that of its emission in the gun and that of its impact on the plate (as evidenced by the blackening of a single grain of photographic emulsion in correspondence of the point of impact). These two events are two quantum jumps. In the interval between these two events, the electron propagates like a wave, as evidenced by the interposition, between the source and the plate, of a screen with a single or double slit. This interposition generates a modulation of the positions of the impacts corresponding, in the case of a single slit, to a diffraction pattern. In the case of a double slit, interference is added to diffraction; therefore, two typically wave-like behaviors. In conclusion, the particle and wave aspects occur in separate instants, and are not co-present in the electron at the same instant. There is therefore, in this sense, no complementarity between the two aspects in quantum processes, but rather alternation.

Therefore, the political choice of complementarity, devised by Bohr to propitiate the confluence of the two schools of thought (matrix and wave) in a single quantum mechanics destined to become a definitive theory, required that attention be diverted from quantum jumps because their existence was obviously in conflict with the proposed idea. Bohr will no longer speak, at least in an interpretative context, neither of quantum jumps nor of the collapse of the wave function throughout his life, starting from the conferences of 1927 for the following thirty years.

Einstein immediately understood, in Brussels, the danger posed by quantum jumps and presented his well-known objection relating to the impact of a particle on a screen: the instantaneous zeroing of the wave function of the particle in all the rest of space was for him a patent violation of the principle of relativity, if the wave was to be understood as a real field in spacetime [1]. Heisenberg's proposal was that it should be understood as a mere mathematical device, and this position makes it clear that according to the spirit of the time what was not contained in spacetime must necessarily be unreal [1].

One may wonder if in 1927 it had been possible to take a different path, that of an *ontology of events*, identified with quantum jumps. This is the reference adopted by the "event-based" version of the theory [9]. As far as philosophy is concerned, such an ontology had been proposed in those years by Russell and Whitehead (see, for example, Russell's "*The Analysis of Matter*" [10]), precisely in connection with the rapid evolution of quantum theory. However, even apart from the aforementioned non-conformity between this possibility and Bohr's objectives, it must be recognized that several obstacles stood in the way of the realization of such a project.

Such a proposal should have answered the question: What causally connects two consecutive quantum jumps? In other words: what is the ontology of the wave function? As Bohr correctly guessed, the answer to such a question could not be found in spacetime alone. It is hardly credible that the community of physicists of the time, educated in a substantialist and object-based vision of matter, could digest the shock of the disappearance of the substance, replaced by a discrete set of events. It is even less credible that this community was willing to welcome a theory that envisaged forms of extra-spatiotemporal causality. For this reason, Bohr's attitude, careful to place the limit of what can be said in correspondence with measurement operations and consequently to banish any conceptual elaboration on "quantum reality", was certainly more prudent and turned out to be, at least for a long historic season, the winning one.

In an era like the present one, marked by a greater openness to discussion (including philosophical) on the principles of physics, and in which string theory has accustomed us to the possibility of multidimensional spaces with dozens of dimensions, perhaps we can be more daring. Here we return to the origins of Bohr's thought and assume the centrality of quantum jumps as a discontinuity of the (otherwise unitary) evolution of the wave function, induced by the simple and known fundamental interactions.

5. Particle-objects vs. particle-events

Before moving on to the conclusions, it seems appropriate to investigate some conceptual issues related to the details of the formalism presented in the previous Sections. The corpuscular aspects of matter are limited, in this formalism, to the sole switching on or off of the wave function; they are mediated by transients in hidden time τ: the well-known quantum jumps. The wave propagation, intermediate between switching on and off, occurs instead in the usual time t of the laboratory and is devoid of corpuscular aspects.

In Section 1 we considered a single plane wave belonging to a wave packet, and we saw how the single infinitesimal intervals of its propagation in time t can be assimilated to jumps at the speed of light along any direction in space. The concatenation of these jumps constitutes a time-oriented trajectory in Minkowski spacetime. The time orientation of the trajectory is inherited from the evolution direction of the plane wave front in Minkowski spacetime. Each elementary segment of this trajectory has an orientation in space which is defined by one of the eigenvalues of the relevant Dirac operator. The trajectory therefore represents a succession of specifications of these eigenvalues. The fact that the plane wave is not an eigenfunction of the Dirac operators implies that the sequence of eigenvalues is in fact not specified, and therefore that the mentioned trajectory is virtual. The trajectories introduced in Section 1 to argue the fuzzyness of the particle's spatial position are therefore not trajectories of any "particle-object". In other words, the position is fuzzy because the propagating entity is a wavefront, not a point with an actual position.

The idea of a particle-object embedded in the wave function immediately leads to problems, in the context of the model discussed here. For example, if the entangled wave function considered in Section 3 "contained" two correlated particle-objects, the specification of the eigenvalue of one of them by an interaction would entail the simultaneous specification of the corresponding eigenvalue of the other. This modification of the physical state of the second particle-object could take place at any distance from the action exerted on the first particle-object, in patent violation of locality. The point here is that this action is not actually exerted on a particle, but on the entire state vector which undergoes, as an effect, the cancellation of one of its branches. This is possible because this action involves the entire three-dimensional physical space, in the manner described in Section 1.

A further problem would arise with the so-called null interactions. Let us imagine a beam of particles directed towards an opaque screen *S*, in which a hole *H* is made. The single particle can impact *S* or pass through *H*, so its state vector, in the formalism proposed here, is described by the expression:

$$| \psi \rangle = \rho_S(\tau_S)A_S| S \rangle + \rho_H(\tau_H)A_H| H \rangle \qquad (18)$$

where $| A_S |^2 + | A_H |^2 = 1$. The instant of incidence on the screen, t_{jump}, can be established with great accuracy by suitably regulating the emission of the particles, even without performing any direct measurement. It therefore happens that while for $t < t_{jump}$ both functions ρ_S, ρ_H are equal to 1, for $t = t_{jump}$ both cancel but only one of them goes back to the initial value 1 as multiplicative factor of the outgoing branch. We will suppose that ρ_S remains zero, *i.e.*, that we have $| \psi \rangle = | H \rangle$ for $t > t_{jump}$. The permanent vanishing of ρ_S can have two causes: an effective interaction which has localized the particle in correspondence with the hole at $t = t_{jump}$, or the absence, at the same instant, of effective interactions between the particle and the screen. In this second case we have a quantum jump induced by a so-called null interaction. In fact, however, this interaction is "null" if referred to a hypothetical particle-object, while it is an effective interaction of the screen *S* with the state vector (18), as evidenced by its dynamics in τ_S, τ_H. If we imagine a particle-object passing through hole *H* undergoing a "null" interaction, this interaction would have the strange property of instantly changing the dynamic state of the particle from $| \psi \rangle$ to $| H \rangle$, inducing -for example- diffraction. This modification, induced by the boundary conditions, would be non-local.

Finally, it must be emphasized that time reversal has very different effects on hypothetical particle-objects and on the state vector. The effect of the operation $t \rightarrow -t$ on a particle-object would be to reverse the path represented by its trajectory. The effect of the time reversal on the state vector is phenomenologically richer, because it implies a change of the initial condition. To continue the example represented by Eq. (18), we can consider the evolution of the conjugate of the post-collapse final state, *i.e.*, $\rho_H(\tau_H)\langle H |$; here we must bear in mind that τ_H varies, at the instant of the jump, from $-\infty$ to 0. The evolution of $\langle H |$ in the inverse time $-t$ generates a state $\langle H' |$ which is different from the conjugate of $| \psi \rangle$. Therefore, in the time interval preceding the crossing of the hole (in the sense of forward time *t*), the physical situation is described by two distinct quantum amplitudes.

6. Conclusions

The "extravagance" of the quantum world seems to be contained in the strange relationship that elementary particles, the ultimate constituents of matter, have with the space-time domain. Here an interpretation is proposed according to which the relationship of particles with space is mediated by time. Furthermore, it is postulated that the time accessible to elementary particles (but not to the systems composed of them) is a complex rather than a real variable. This proposal is consistent with a definition of the level of elementary particles as the level of physical reality on which quantum discontinuity manifests itself, *i.e.*, the phenomenon of quantum jumps. In this sense, the existence of a level of elementary constituents of matter becomes a constitutive factor of quantum theory.

The salient point is that at the level of elementary particles, in the quantum jumps in which they are involved as a result of their interactions, a peculiar relationship between vacuum and space comes into play. The particles are conceivable as deformations of this vacuum, which manifest themselves in the usual temporal domain as oscillatory phenomena (the de Broglie phase) involving the entire physical space. What we mean by the "corpuscular aspect" of the particles are basically the transients associated with the initiation and damping of these phenomena. These transients do not occur in the usual time: the relevant evolution parameter is an imaginary time. It is plausible that these transients originate from the localization of the charges - associated with the particles - in the usual time domain. However, the details of a mechanism of this type must be provided by a specific theory of quantum jumps, the formulation of which goes beyond the objectives of the present work.

Regardless of the model, the vacuum must be understood here not as a classical ether, that is, as an all-pervading substance distributed in space and persistent in time. Rather, it must be thought of as a pre-spatial and pre-temporal form of matter, connected to the spatiotemporal domain through the deformations constituted by elementary particles.

A model that implements this general reasoning is the one that, through a particular geometric reading of the Higgs mechanism, describes elementary particles as micro-universes tangent to ordinary spacetime [11]. The point of tangency represents the labeling, through space-time coordinates, of the deformation of the vacuum constituting the micro-universe. In this representation, according to a third quantization description, the non-deformed vacuum corresponds to the absence of particles and the micro-universes that describe them, therefore to a "void" with no relationship to space-time. The model allows a deduction of the relations (1)-(4) which constitute the starting point of the present reasoning.

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