Short Communication

On the Two Spaces of Elementary Particles, and Why Wave Functions Collapse

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The current formulation of quantum theory is notoriously agnostic about the ontological aspects of the propagation of elementary particles and their interactions. In this brief note, we propose a minimal ontological representation of interactions, based on a micro-cosmological description of the manifestation of these particles in the collapse events of their wave function. The fading of the pre-collapse wave function and the arising of the post-collapse function occur dynamically, as they asymptotically approach different sheets of the same micro-cosmological horizon, whose projections onto ordinary spacetime are placed at finite times.

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1. Introduction

The current formulation of quantum theory is notoriously agnostic about the ontological aspects of the propagation of elementary particles and their interactions. In particular, the standard formulation of the theory inherited from the original treatises of Dirac, Von Neumann, and Fock [1][2][3] does not specify the nature, epistemic or ontological, of the collapse of the wave function, nor does it highlight any relation between the collapse and discontinuous interactions between material fields (the so-called quantum jumps). This lack of specification has given rise to a debate that continues to this day. This short article has three objectives: 1) to support an ontological interpretation of collapse as a reflection, on Hilbert space, of a real physical process consisting of a micro-interaction between elementary particles; 2) to show, through a specific model, how the current formulation of quantum theory expresses the discontinuous nature of such micro-interactions; and 3) to provide arguments in support of a logically closed construction of quantum theory, based on the fundamental nature of the concept of an elementary particle as a minimal package of physical quantities involved in individual micro-interactions. Such a construction—which in this article we leave as an open possibility for the future—would not require the pre-existence of "observers" as a theoretical requirement and would make clear the emergence of the classical macroscopic level from the quantum microscopic one.

The proposed model, merely for illustrative purposes of the above argument and without any claim to correspond to physical reality, is based on the following three assumptions: 1) when an elementary particle is involved in a discontinuous variation of its dynamical state (quantum jump) due to a micro-interaction (even if null), it manifests as a de Sitter space tangent to spacetime; 2) the pre-collapse wave function is the probability amplitude of the point of tangency, which is quantum delocalized; and 3) after the manifestation of the de Sitter space, the evolution of the pre-collapse wave function continues without any "stop," but the evolution parameter becomes the internal time of the de Sitter space. The same behavior is assumed for the complex conjugate of the post-collapse wave function.

In this regard, the transition $\psi \to \varphi$ (where ψ and φ denote the pre- and post-collapse wave functions, respectively) is interpreted as the asymptotic approach of ψ and φ^* to the two distinct sheets of a micro-cosmological de Sitter horizon, whose spacetime projection comes to constitute a pair of absorbing barriers at finite times.

The evolution parameter is modulated by the micro-interaction in which the individual particle participates, which makes it distinct for each particle and for each experimental run. The presence of absorbing barriers to the wave propagation of the particle leads to the fading of ψ (and the buildup of φ) in the external time of the laboratory. From this point of view, the mechanism of the wave function collapse appears to be, in some ways, similar to that of the gravitational collapse of matter near a black hole: while the duration of the collapse is infinite for a distant observer (the falling matter asymptotically approaches the event horizon), it is finite for the freely falling observer with no proper motion. In the present situation, on the other hand, the collapse ends in a finite interval of external laboratory time, while in the internal time of de Sitter space, no collapse occurs.

The introduction, in the present context, of the causal structure represented by a de Sitter microspace on the scale of elementary particles is motivated by the need to describe the exchange of four-momentum with other particles at the micro-interaction vertex. That is, to describe the real physical event that is associated with the collapse of the wave function in Hilbert space. This event constitutes, in this sense, the cause of the collapse. According to this approach, a distinction must therefore be made between the physical event, represented by the exchange, and its formal description, represented by the collapse. From this point of view, our position is similar to that expressed by Heisenberg in his famous work of his mature years [4]. In our opinion, however, the non-separability of entangled states prevents a purely epistemic conception of the collapse.

The proposed model is illustrated in Section 2; as emphasized in the final paragraph of this section, it is a simplified and summarized version of previously published works. This simplification aims to highlight the micro-cosmological nature of collapse and its relationship with elementarity. This relationship is further emphasized in Section 3. In Section 4, devoted to Conclusions, we highlight some issues that are only briefly touched upon in this work and remain in the background, and we refer to works where they are explicitly addressed from a broader perspective.

2. The model

2.1. Single particle

Let us consider a particle of mass M and charge q (here we mean the completely renormalized values of these two quantities). By "charge" we do not necessarily mean the electric charge, but the charge with which the particle couples more strongly to the interaction fields of which it is the source. Thus, for a neutrino, it will be the weak charge; for a charged lepton, the electric charge; for a quark, the strong charge. The quantities q and M considered here are fully renormalized; they are therefore those that a particle possesses as an element of an asymptotic state entering (or exiting) an interaction vertex. This vertex therefore represents a real micro-interaction, in which the particle exchanges physical quantities with other particles or field quanta, also entering (or exiting) the vertex as asymptotic states. It is to micro-interactions of this type that the discontinuous variations in the temporal evolution of the particle's wave function, known as *quantum jumps* or *collapses*, are associated.

We postulate that in such events the particle manifests itself in the form of a de Sitter space (dS) tangent to spacetime. The reason for this assumption is that we intend to constrain the collapse of the wave function to the exchange of physical quantities, carried by the particle, with other particles or fields. We will focus in particular on the four-momentum, and for brevity we will refer to the exchange in question as "the impact". However, the reasoning will be easily extendable to any other physical quantity (spin, isospin, etc.). The line of reasoning is as follows: the impact is associated with the creation of a space dS tangent, at its point O, to the spacetime V^4. The gnomonic projection of dS onto V^4 constitutes a so-called "Castelnuovo chronotope" [5][6], as illustrated by Figures 1 and 2. A well-known feature of this projection is

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the existence of a Cayley-Klein absolute [5][7] (Figure 1). We choose on dS a frame whose time axis is transformed, by the gnomonic projection, onto the time axis of the external frame t chosen by the observer. We denote with τ, where $\tau \in (-\infty, +\infty)$, the time coordinate on this axis of dS and assume $\tau = 0$ in O. A notable property of the gnomonic projection is that while the original dS space is infinitely extended along the temporal direction and finite and closed along the spatial directions, exactly the opposite holds for the Castelnuovo chronotope. In particular, the following geometric relation holds [8]:

$$\tau = \frac{c\tau_0}{2}\log\left[\frac{c\tau_0 + (t - t_0)}{c\tau_0 - (t - t_0)}\right] \tag{1}$$

Here t_0 is the time coordinate of the instant of collapse, in the external time t. Since $-\infty < \tau < +\infty$, from (1) we have $-c\tau_0 \leq t - t_0 \leq +c\tau_0$. The quantity $r = c\tau_0$ is the so-called "de Sitter radius" of the dS space.

Let now $O' = O'(\tau)$, with $O'(0) = O$, be the current point on the τ-axis of the dS space. Recall that O is the point of tangency of dS on V^4. We postulate the existence, on the hyperplane tangent to dS in O′, of two distinct vector fields y_μ ($\mu = 0, 1, 2, 3$), applied in O′ and having their endpoint free on the absolute. These vectors will therefore satisfy the equation $y_\mu y^\mu = r^2$ and, starting from them, it will be possible to define two distinct vector fields $p_\mu = (M/\tau_0)y_\mu$ applied in O′. As can be seen immediately, $p_\mu p^\mu = M^2c^2$. For $\tau = 0$ the hyperplane tangent to O′, which in this case coincides with O, is also tangent to V^4 and the p_μ vectors can then be interpreted as the two four-momentum fields of the particle respectively associated with the forward $\phi(p_\mu, t_0)$ and backward $\lambda^*(p_\mu, t_0)$ probability amplitudes in the momentum space. The difference between $\phi(p_\mu, t_0)$ and $\lambda(p_\mu, t_0)$ represents the quantum description of the impact.

If $O'(\tau)$ is translated into O, the two vector fields $p_\mu(\tau)$ will be associated with the functions $\phi(p_\mu, t)$, $\lambda^*(p_\mu, t)$, where $t = t_0 + (t - t_0)$. In this relation, $(t - t_0)$ is connected to τ by Eq. (1). Therefore, for the function $\phi(p_\mu, t)$, with $t > t_0$, we have $t_0 < t < t_0 + \tau_0$; for the function $\lambda^*(p_\mu, t)$, with $t < t_0$, we have instead $t_0 - \tau_0 < t < t_0$. There are no restrictions on the time domain of these functions for $t < t_0$ and $t > t_0$ respectively. In these intervals, the functions $\phi(p_\mu, t)$, $\lambda(p_\mu, t)$ have the usual meaning of pre-collapse and post-collapse functions in momentum space, respectively. Their Fourier conjugates are the usual pre-collapse $\psi(\boldsymbol{x}, t)$ and post-collapse $\varphi(\boldsymbol{x}, t)$ positional wave functions, respectively. The existence of these functions shows that O (the "position" x_μ of the particle at the instant of collapse) is also delocalized on V^4, as is the four-momentum.

However, extending the domain of the aforementioned functions to the intervals $t > t_0$ and, respectively, $t < t_0$, represents a novelty compared to the ordinary narrative. The evolution of these functions in the internal time τ of the space dS is an evolution free from external forces, induced simply by the dispersion of the wave packet. Since the "debordement" is measured by the parameters τ_0, $r = c\tau_0$, it becomes important to estimate their value. We can observe that the minimum energy required by the uncertainty principle to temporally resolve the interaction ($\hbar/\tau_0$), multiplied by the interaction constant $q^2/\hbar c$, must provide the *minimum* energy released by the particle at the interaction vertex, i.e., its rest energy Mc^2. We therefore have:

$$r = \frac{q^2}{Mc^2} \tag{2}$$

which coincides with the classical radius in the case of a charged lepton. In the case of a hadron, assuming phenomenologically $q^2 \cong \hbar c$, we have $r \cong \hbar/Mc$. These expressions reasonably fix a scale of elementary particles. Although the particle is spatially point-like, in the sense that the only contact between its internal dS space and spacetime is at point O, it has an extension in the five-dimensional real space E^5 in which both dS and V^4 are immersed. The spacetime trace of this extension is constituted by the finite interval $-c\tau_0 \leq t - t_0 \leq +c\tau_0$ beyond which the pre- and post-collapse functions become zero. This statement is valid in any spacetime frame, because a Poincaré transformation on V^4 induces on dS a de Sitter transformation that leaves τ_0 unchanged. The discontinuous variation of the dynamical state of a renormalized particle thus requires a time on the order of τ_0, the "chronon" that Caldirola introduced—with the same purpose—in his classical theory of the electron[9][10].

In other words, the parameter τ_0 measures the inertia that the function ψ (φ^*) opposes to its projection on the function φ^* (ψ). The finiteness of τ_0 expresses the concept that this projection is not a mere mathematical operation that translates a change in the particle state knowledge by some observer, but an objective dynamical process that occurs in a finite time derivable from the coupling constant $q^2/\hbar c$ and the particle rest mass M. The inertia measured by τ_0 is implied by the existence of virtual processes underlying the renormalized particle, the temporal extension of which (Compton time) is proportional to M^{-1}; the behavior $\tau_0 \propto M^{-1}$ is therefore quantum in nature. The decoherence associated with the collapse manifests itself on the time scale τ_0, which becomes negligible in the classical limit $h/M \to 0$; this suggests that such decoherence constitutes the real reason for classicalization[11]. Three observations seem pertinent and appropriate:

1. The vectors $p_\mu(\tau)$, with $\tau \neq 0$, do not satisfy the dispersion relation on spacetime (although they satisfy it in the hyperplane tangent to dS in $O'(\tau)$), since they have a non-zero component along the fifth coordinate of E^5. This is precisely the trademark of virtual processes.

2. The natural scale of the moments within the dS space is $\hbar/c\tau_0$. Multiplying this scale by the interaction constant $q^2/\hbar c$, according to the same reasoning that led to Eq. (2), we obtain Mc, which is the norm of the momentum four-vectors. The spatial scale of the dS space, i.e., r, multiplied by the reciprocal $\hbar c/q^2$ of the interaction constant, gives the Compton scale $\hbar/Mc$ at which the virtual dissociations and recombinations associated with the interaction vertex manifest themselves. This is also the minimum scale of spatial delocalization of O (in general, such delocalization is expressed by the spatial region where $\psi(\mathbf{x}, t_0)\varphi^*(\mathbf{x}, t_0) \neq 0$). The product of the two scales is, of course, $Mc \times \hbar/Mc = \hbar$.
3. The gnomonic projection of ψ (φ) for $t > t_0$ ($t < t_0$) is limited, on V^4, to a time interval $\approx \tau_0$. This interval is smaller than or equal to the Compton scale $\hbar/Mc^2$ at which the concept of a wave function loses meaning due to the virtual dissociations and recombinations of particle-antiparticle pairs. Therefore, the above-mentioned temporal debordements of the evolution of these functions have no effect on the predictive level.

In our argument, we have considered wave functions consisting of single probability amplitudes, that is, the case of spinless scalar particles. However, the generalization to the case of any spin does not seem to present any obstacles. In the case of a particle with total spin $s \neq 0$, the point O will be associated with $2s+1$ probability amplitudes ($2(2s + 1)$ in the relativistic case), each associated with a separate four-momentum field, which will constitute the components of a Pauli spinor (a Dirac spinor in the relativistic case). The following reasoning will be limited to the scalar case only, but the generalization to particles with spin is easily obtained by replacing the scalar products of wave functions with the scalar products of spinors.

It is worth repeating that the dS space is not associated with the particle throughout its entire spacetime propagation, but only at the extremes of this interval, that is, in the micro-interactions that determine the beginning and end of this propagation. In correspondence with these micro-interactions, the particle, which is itself nothing more than a packet of conserved physical quantities with a certain statistical distribution of actualization, exchanges these quantities with other particles (or gauge quanta). The dS space is connected to the expression of this exchange and exists only contextually with it. In other words, the dS space is connected to an ontological representation of the exchange (impact), which constitutes the *objective* physical event related to the collapse.

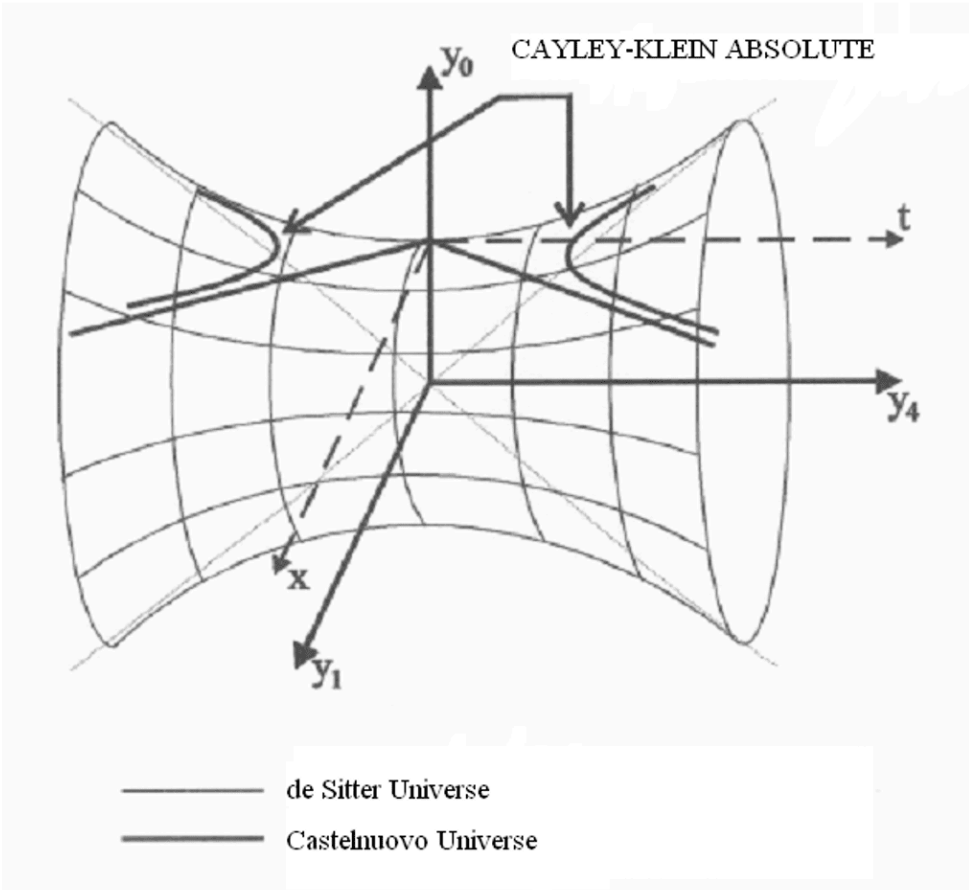

Figure 1. Relationship between de Sitter space and its gnomonic projection, the Castelnuovo space.

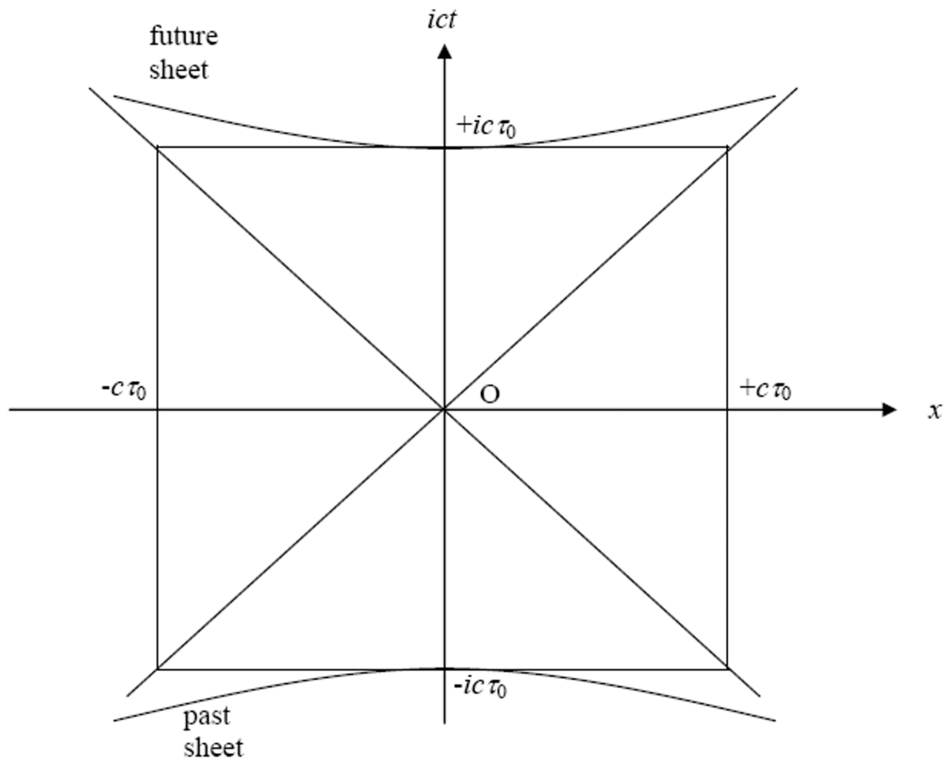

Figure 2. Castelnuovo spacetime, with its light-cone and its de Sitter horizon. O is the tangency point on spacetime.

2.2. On the possible physical interpretation of dS space

The internal metric of the de Sitter-Castelnuovo chronotope is induced by the gnomonic projection of the dS space onto V^4 and is different from the Minkowski metric. It describes the way in which a hypothetical observer located in O coordinates *remote* events within the chronotope. The relevant theory of relativity is therefore not Einstein's, but the so-called de Sitter's[12][13]. The two theories coincide in the local limit.

A particularly important element in this context is constituted by the variation of the value of the mass. The mass remains constant for the observer located in $O'(\tau)$, that is, with respect to the local clock that marks the time τ; its constant value is the local value M measured in O. However, in the fixed reference having as its origin O, the mass varies with τ, and it vanishes on the Cayley-Klein absolute (that is, on the two sheets, past and future, of the de Sitter horizon of O). In other words, there is a projective effect on the values of the mass that O can infer on the basis of the symmetry group acting in the chronotope (which is the de Sitter group, not the Poincaré group of Einstein's ordinary relativity[12][13]).

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The projective cancellation of the mass “seen from O” on the two sheets, past and future, of its de Sitter horizon suggests a simple physical interpretation of the dS space, which is the following: the parameter τ is nothing but another name for the “apparent” mass $M'(|\ \tau\ |)$, with $M'(0) = M$ and $M'(\infty) = 0$. The evolution of ψ for $t_0 < t < t_0 + \tau_0$ represents the transient associated with the fading of the renormalized mass M on V^4 and the consequent restoration of the vacuum state. Similarly, the buildup of φ for $t_0 - \tau_0 < t < t_0$ represents the establishment of the renormalized mass starting from the original vacuum state. The dS space is, in other words, a model of the transfer of mass M to the leaving state φ and its removal from the entering state ψ. The radius of curvature $r = c\tau_0$ of this space measures the duration τ_0 of the transients associated with these processes on V^4. The duration of the interval $(-\tau_0, +\tau_0)$, centered on O, is generally different from the minimum time scale on which O is delocalized, i.e., the Compton scale $\approx\hbar/Mc^2$ on which the particle is renormalized. This interpretation is consistent with the “inertial” nature of the r (or τ_0) scale underlined in the previous subsection.

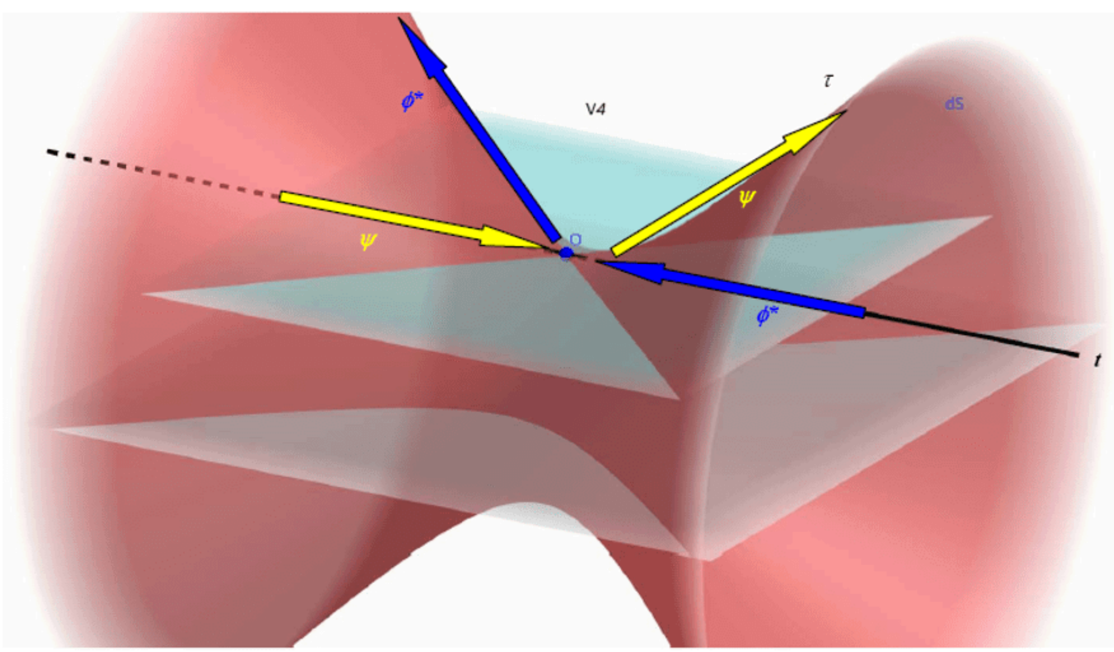

Figure 3. In this three-dimensional representation of E^5 space, dS space is colored red, while the V^4 space tangent to it at O is colored light. The timeline of the pre-collapse wavefunction in the past light cone of O on V^4 is the t-axis; after O, it becomes the positive portion of the τ-axis in dS (yellow arrows). Analogously, the timeline of the conjugate post-collapse wavefunction in the future light cone of O on V^4 is the t-axis; before O, it becomes the negative portion of the τ-axis in dS (blue arrows).

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The change in the time axis as a result of crossing O is illustrated in Figure 3. Note that while t is the time *external to the events*, and in which the latter are placed, τ is instead the internal time of the event $\psi \rightarrow \varphi$. It, therefore, does not mark further events. This implies that the evolution of the function ψ (φ) for $\tau > 0$ ($\tau < 0$) is free. However, the interpretation of $|\psi|^2$ ($|\varphi|^2$) as the *statistical weight* of the configuration of positions or moments remains unchanged.

It is also noteworthy that while there is a unique time domain t, as it is not peculiar to any specific event occuring in it, the time τ instead takes the label of the specific particle involved in the micro-interaction that induces a specific collapse.

The point seems to be that the variable t defines the distance between *actualized* events and is therefore — in a logical sense—consequent upon their actualization. If one were to dispense with actualization, the t-domain would not exist except in a purely potential sense. The collapse is therefore the passage between two different temporal references: one in which the expected event is placed in relation to other already actualized events or that will be actualized (t), and one in which no events are expected anymore and the evolution of the four-momentum fields, spin, etc., is described in the temporal reference of the already actualized event (τ). In other words, the chronological distance measured by t arises as a consequence of actualization, just as the distance between two sodium atoms in a salt crystal, measured in lattice steps, is defined by the formation of the crystal and does not pre-exist that formation.

2.3. More particles

For a system of N particles with spatial coordinates $\boldsymbol{x}_i$, $i = 1, 2, ..., N$, the wave functions involved will be $\psi(\boldsymbol{x}_1, \boldsymbol{x}_2, ..., \boldsymbol{x}_N; t)$ and $\varphi^*(\boldsymbol{x}_1, \boldsymbol{x}_2, ..., \boldsymbol{x}_N; t)$. Let us suppose that particle 3 participates in a micro-interaction. The wave function ψ will, in general, be expressible as the product of a wave function ψ_1, dependent on the coordinates and spins of particles independent of particle 3 and uncorrelated with it (which we symbolically denote by z_1), and a wave function ψ_2, dependent on the coordinates and spins of particle 3 and of the particles correlated and/or interacting with it (which we symbolically denote by z_2). In other words:

$$\psi(z_1, z_2; t) = \psi_1(z_1; t)\psi_2(z_2; t) \tag{3}$$

The collapse associated with the micro-interaction at t_0 can be described as follows:

$$\psi(z_1, z_2; t) \rightarrow \psi_1(z_1; t)\psi_2(z_2; \tau > 0) \tag{4}$$

$$\varphi * (z_1, z_2; t) \rightarrow \psi_1 * (z_1; t)\varphi_2 * (z_2; \tau < 0) \tag{5}$$

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And, for $t > t_0$:

$$\varphi(z_1, z_2; t) = \psi_1(z_1; t)\varphi_2(z_2; t) \tag{6}$$

Only the functions ψ_2, $\varphi_2{}^*$ are modified by the micro-interaction. The functions $\psi_2(z_2; \tau > 0)$, $\varphi_2{}^*(z_2; \tau < 0)$ disappear in time intervals of value τ_0. It is noteworthy that the micro-interaction involves not only particle 3 but all the particles that are entangled with it. The change in the time evolution parameter from t to τ involves all these particles, even those that do not directly participate in the micro-interaction, such as particle 3. This result, which is the basic feature of the EPR (Einstein-Podolski-Rosen) phenomenon[14], demonstrates that particles are not individual entities pre-existing interactions but bundles of conserved physical quantities (energy, momentum, spin) that are distributed among multiple interaction vertices.

To illustrate the point, let's consider the particular case:

$$\psi_2(z_2, t) = [\xi_a(x_1, t)\xi_b(x_3, t) + \xi_b(x_1, t)\xi_a(x_3, t)]/2^{½} \tag{7}$$

$$\varphi_2(z_2, t) = \xi_a(x_1, t)\xi_b(x_3, t) \tag{8}$$

where the functions $\xi_{a,b}$ are orthonormal. Let us assume that it is particle 3 that is subject to the micro-interaction. The dS space associated with the impact undergone by particle 3 will have O as the point of tangency on V^4, and O will be delocalized on V^4. The amplitude entering O will then be $\psi_2(z_2, t)$, while the amplitude exiting O will be $\varphi_2(z_2, t)$. These amplitudes will enter and exit O as states of particle 3 ($\xi_a(\boldsymbol{x}_3, t)$, $\xi_b(\boldsymbol{x}_3, t)$) modulated by terms dependent on $\boldsymbol{x}_1$ ($\xi_a(\boldsymbol{x}_1, t)$, $\xi_b(\boldsymbol{x}_1, t)$). Given the orthogonality of the exiting amplitude $\varphi_2(z_2, t)$ and the second term of $\psi_2(z_2, t)$:

$$\langle \varphi_2(z_2, t) | \xi_b(x_1, t)\xi_a(x_3, t) \rangle = 0 \tag{9}$$

only the incoming amplitude $\xi_a(\boldsymbol{x}_1, t)\ \xi_b(\boldsymbol{x}_3, t)$ actually contributes to the process. The impact in O is therefore given by the (null) difference between the incoming and effective function $\xi_b(\boldsymbol{x}_3, t)$ and the outgoing function $\xi_b(\boldsymbol{x}_3, t)$. These functions are modulated, at the input and output, by the factor $\xi_a(\boldsymbol{x}_1, t)$ depending on $\boldsymbol{x}_1$. The impact statistics is actually defined by the marginal probability density function:

$$\xi_b(x_3, t)\xi_b * (x_3, t) \int dx_1 \xi_a(x_1, t)\xi_a * (x_1, t) = |\xi_b(x_3, t)|^2 \tag{10}$$

As can be seen, the description would remain completely unchanged if particle 1 were involved in the impact, rather than particle 3, as long as the outcome was still expressed by $\varphi_2(z_2, t)$. The only difference would be that, in this case, the impact would be given by the (null) difference between the incoming and effective function $\xi_a(\boldsymbol{x}_1, t)$ and the outgoing function $\xi_a(\boldsymbol{x}_1, t)$. These functions would be modulated, at the input and output, by the factor $\xi_b(\boldsymbol{x}_3, t)$ depending on $\boldsymbol{x}_3$.

The collapse $\psi \to \varphi$ can be induced either by an interaction or by the absence of interaction (a situation often referred to as a “null interaction”). An example is the ψ of a single particle incident on a screen opaque to its propagation, in which a slit is made; in this case, φ is the wave function of the particle downstream of the screen. If the slits are multiple, φ is the superposition of the waves transmitted by the individual apertures; this leads to the well-known phenomena of self-interference. The notion of “impact” introduced here as a modification of the four-momentum distribution, not localized in the form of a corpuscular carrier, is general enough to be suitable for these situations as well.

In this paper, we propose a simplified version of what a more complete quantum mechanical description should be. However, without going into details, one can mention the possibility of a broader perspective, in which the particle de Sitter space dS is *quantum*, and the functions ψ, φ are constructed from the wave function of this space[15]. The parameter t can then be connected to the internal cosmic time of this space even in the phase of unitary evolution. This connection is natural: in de Sitter space, the slice defined by a specific value of the internal time contains the point that will become a point of tangency on spacetime following a collapse at that instant. That slice then labels both the *internal* and *external* time instants at which the collapse is manifested. In this perspective, the collapse comes to consist in a change of the metric signature, which determines the passage from a de Sitter space to a Euclidean instanton (or vice versa). For a detailed explanation that goes beyond the scope of this presentation, we refer to reference[15].

3. Discussion

The probability amplitude of a quantum system is normally expressed as a function of its Lagrangian coordinates. These define the system's configuration at a given level of description. However, from a fundamental point of view, every physical system is composed of elementary particles, and therefore the most complete version of the wave function is one in which the dependence on the spatial coordinates of the constituent particles is made explicit. It is to this version, which we can write in the form $\psi(\mathbf{x}_1, \mathbf{x}_2, ..., \mathbf{x}_N; t)$, that the previous description of the collapse applies. If this description is assumed to be true, it therefore identifies a level of elementary particles as the level of the physical entities individually involved in the collapse. Thus, the notion of "elementary particle" as the agent of the individual "click" becomes central to quantum theory, a point that is not taken into account in the usual formulation of the theory. This vacancy has a simple historical explanation: quantum theory was assumed to be definitive and complete during the Fifth Solvay Congress in 1927[16], and at that time the world of elementary particles was largely unknown. In fact, the existence of only the electron, the proton, and, quite recently, the photon

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was known[17]. Elementary particle physics seemed to be—at most—a potential field of application of the recently formulated theory for atoms and molecules. The idea that the notion of elementary particle should be included in the axiomatics of the theory itself was not a topic of discussion.

To avoid a possible misunderstanding, it's important to note that connecting collapse with the existence of a level of elementary particles as entities individually involved in it *does not identify* that level. This is where theory faces experimental practice. Currently, the "elementary particles" are understood to be leptons, quarks, and gauge quanta of the Standard Model. Therefore, if we direct a single electron at a fluorescent screen and observe its scintillation, we are led to interpret it as an aspect of the interaction between the incident electron and, say, an electron on the screen. This interpretation, however, only makes sense in a specific historical context. If a hypothetical composite nature of electrons (in terms of real constituent particles interacting independently with particles external to the electron to which they belong) were to be ascertained at CERN, that same collapse would have to be reinterpreted as an aspect of the interaction between the elementary constituents of the two electrons mentioned, and therefore the "level of elementary particles" would move down in the combinatorial hierarchy of physical systems.

According to our proposal, an "elementary particle" is a minimal package of physical quantities that can be actualized in the collapse of a wave function. The directly experiential aspect of the collapse is the *impact*, i.e., the exchange of physical quantities (four-momentum in the example considered) between the particle in question and other particles or fields. This phenomenon is spatiotemporal and is described by the difference between the particle's four-momentum distributions associated with the pre- and post-collapse functions, respectively.

Given its plausibly informational nature[18], it is possible to consider the wave function as a statistical-mathematical tool, exactly like the partition function in statistical mechanics (the two functions, moreover, are connected by a mathematical operation, which is Wick rotation[19]). Consequently, it is possible to interpret the collapse of the wave function in epistemic terms. It should be noted, however, that in the presence of entanglement, the collapse preserves the correlations between impacts. This observation seems to indicate a physical reality of a "multiplex" type, not directly observable, somehow underlying the wave function or hidden behind it. Such a concept of reality can be captured only by renouncing the exhaustiveness of the spacetime description, as in the approach reported in[15]. The dependence of the wave function on the positions of the impacts and on the evolution parameters of the individual particles leads spontaneously to conceiving a precursor of spacetime contained within each particle, from which the usual spacetime emerges as an effect of the local nature of the interactions

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(diagonality of the interaction operators in the coordinate representation), i.e., as a sort of trace-space. This possibility is investigated in detail in[20]. The elucidation of these issues, however, lies beyond the limits of the present paper.

The topic of quantum jumps and their connection with the collapse of the wave function has been the subject of two recent articles by Tadashi Nakajima[21][22], which share the perspective adopted in the present work. In particular, Nakajima correctly defines the process we simply indicate as “quantum jump” as “Microscopic Quantum Jump”. The point, in fact, is that the jump involves elementary particles and not a single particle interacting with a macroscopic object as a whole. Nakajima's work is complementary to ours in the sense that he does not propose any specific mechanism for the MQJ, while this is exactly the aim of the present paper. On the other hand, we completely ignore the possible phases of MQJ amplification and transduction implied, for example, in the quantum measurement process and in the consequent collapse of the wave function of the total system apparatus+microentities. We recommend that readers interested in these topics read the references[21][22], which constitute a comprehensive exposition.

4. Conclusions

Quantum theory arose in connection with the development of microphysics, as a theoretical support for understanding systems such as atoms and molecules. In this sense, its construction was, from the outset, a search for a language that would embrace the challenge of elementarity, implied by the atomic structure of matter. However, the formulation of powerful quantization tools applicable, in principle, also to macroscopic systems, and the time lag between the construction of the theory and the development of particle physics, obscured the fundamental role of elementarity, which does not appear as a constructive principle in the axiomatization of the mature theory. The consequence of all this has been the divorce between the collapse of the wave function and microphysics (the impacts of elementary particles or ″quantum jumps″). This divorce leaves the nature of the collapse undetermined in the current formulation. It appears to be independent of interactions, and its formal representation through projection operators does not address this difficulty. In particular, it fails to highlight the fact that the collapse fixes a scale of the physical world at which it occurs: that of elementary particles. In turn, this concealment creates the problem of the emergence of the classical level from the underlying quantum level.

An even more devastating effect has been the tendency to construct representations of the theory that do not include collapse or that reduce it to its merely epistemic aspects. These range from traditional pilotwave theory and Bohmian mechanics to relative states, all the way to QBism and modern relationism. Others, in reaction, have developed models that invoke phenomena of "spontaneous" localization or objective collapses mediated by unusual interactions, different from the ordinary ones known in particle physics. Our suggestion is to reconsider quantum theory in light of the results of experimental physics over the past century, which irrefutably demonstrate the importance of the atomic structure of matter, both spatially (the existence of minimal units of "substance" identified in elementary particles) and temporally (the discrete nature of events, or collapses). Our hope is that, with our proposal, we have provided a different perspective on these difficult questions.

References

1. ^*Dirac PAM (1958). The Principles of Quantum Mechanics. Oxford, UK: Clarendon Press.*
2. ^*Von Neumann J (2018). Mathematical Foundations of Quantum Mechanics. Princeton, USA: Princeton University Press.*
3. ^*Fock VA (1978). Fundamentals of Quantum Mechanics. Moscow, USSR: MIR.*
4. ^*Heisenberg W (1959). Physics and Philosophy. The Revolution in Modern Science. London: Ruskin House.*
5. a, b*Castelnuovo G (1930). "L'universo di de Sitter" [De Sitter's Universe]. Rend Accad Lincei. **12**:263.*
6. ^*Castelnuovo G (1931). "De Sitter's Universe and the Motion of Nebulae." MNRAS. **91**(8):829–836.*
7. ^*Arcidiacono G (1988). "L'universo di de Sitter, il gruppo di Fantappié e la cosmologia del big bang" [De Sitter's Universe, Fantappié's Group and Big Bang Cosmology]. Collect Math. **39**:55–65.*
8. ^*Fantappié L (1954). "Su una nuova teoria di "relatività finale"" [On a New Theory of "Final Relativity"]. Rend Accad Lincei. **17**(5):158–165.*
9. ^*Caldirola P (1979). "A Relativistic Theory of the Classical Electron." Riv Nuovo Cim. **2N13**:1–49. doi:10.1007/BF02724419.*
10. ^*Benza V, Caldirola P (1981). "De Sitter Microuniverse Associated to the Electron." Nuov Cim A. **62**:175–185. doi:10.1007/BF02770909.*
11. ^*Chiatti L (2020). "Bit from Qubit. A Hypothesis on Wave-Particle Dualism and Fundamental Interactions." Information. **11**:571. doi:10.3390/info11120571.*
12. a, b*Arcidiacono G (1988). "L'Universo di de Sitter, il gruppo di Fantappié e la cosmologia del big bang" [De Sitter's Universe, Fantappié's Group and Big Bang Cosmology]. Collect Math. **39**:55–65.*
13. a, b*Licata I, Chiatti L, Benedetto E (2017). De Sitter Projective Relativity. Heidelberg, Germany: Springer.*

14. ^*D'Espagnat B (2018). Conceptual Foundations of Quantum Mechanics. Boca Baton, USA: Taylor & Francis.*
15. a, b, c*Chiatti L (2025). "Higgs Mechanism, Elementary Particles and Quantum Foundations: A Geometrical Connection." J High Energy Phys Gravit Cosmol. **11**:1374–1417. doi:10.4236/jhepgc.2025.114086.*
16. ^*Bacciagaluppi G, Valentini A (2009). Quantum Theory at the Crossroads: Reconsidering the 1927 Solvay Conference. Cambridge, UK: Cambridge University Press.*
17. ^*Baggott J (2011). The Quantum Story: A History in 40 Moments. Oxford, UK: Oxford University Press.*
18. ^*Chiatti L (2024). "Wave Function and Information." Quantum Rep. **6**:231–243. doi:10.3390/quantum6020017.*
19. ^*Sakurai JJ (1984). Advanced Quantum Mechanics. Menlo Park, USA: Benjamin.*
20. ^*Chiatti L (2023). "Parity Violation as a Possible Indication of a Pre-Spatial Order Underlying the Standard Model." Int J Quant Found. **9**:158–173.*
21. a, b*Nakajima T (2023). "Microscopic Quantum Jump: An Interpretation of Measurement Problem." Int J Theor Phys. **62**:67. doi:10.1007/s10773-023-05326-8.*
22. a, b*Nakajima T (2024). "Relation Between Quantum Jump and Wave Function Collapse." Qeios. **6**:1–7. doi:10.32388/DCB5P3.3.*

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