Article

Quantum jumps revisited

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Abstract: A theoretical description of quantum jumps at the level of elementary particles is proposed, based on a micro-cosmological interpretation of their de Broglie phase. The third quantization formalism proposed in current literature for the description of baby universes in quantum cosmology is used here to describe the breakdown of unitarity in the transition from the pre-jump to the post-jump wave function. The corpuscular aspect manifested by the particle in the micro-interaction that originates the jump is represented by a pair of evanescent "micro-universes", respectively pre- and post-jump, connected by a wormhole. The latter represents the actual implementation of the interaction that leads to the projection on the outgoing state; this interaction is always local, even when the selected outgoing state is entangled. Therefore, the decoherence which leads to the emergence of classicality is originated by the same fundamental interactions of the Standard Model involved in the unitary evolution of the wave function. The objective nature of the reduction process admits implications on the possibility of using the formalism in the cosmological context, which are briefly discussed.

Keywords: de Broglie phase; de Sitter geometry; micro-cosmology; third quantization; Higgs mechanism

1. Introduction

One of the most disconcerting discoveries in physics of the last century was undoubtedly that of the wave nature of material particles. De Broglie introduced, around 1923 [1], his conception of an internal "clock" associated with each particle, which can be represented by a "phase wave" $\exp(\pm i\omega t)$; in this expression $\omega = mc^2/\hbar$, where m is the particle mass and t its proper time. This phenomenon today takes the name of "de Broglie oscillation" or "de Broglie phase". Its discovery poses the still unsolved problem of explaining how the two natures of a particle, the corpuscular one (involved in the processes of emission and absorption) and the wave one (relevant in the propagation interval), can be harmonized with each other. These two natures are interconverted in quantum jumps, non-unitary transformations of the quantum amplitude of the particle described by the quantum formalism by means of projection operators [2], but of which there is no shared dynamic theory. The objective of this paper is to propose one, which we present at the highest possible level of detail: that is that of elementary particles, using this term in the current meaning that includes leptons, quarks, hadrons and gauge bosons (although for simplicity we we will focus on charged leptons and hadrons). According to our thesis, it is in fact at this level that the wave function reduction process takes place.

The hypotheses underlying the proposal are presented in Section 2, which describes the possible connection between the de Broglie phase factor and a micro-cosmological

description of elementary particles [3-9]. This Section defines the time variables used to describe the dynamics of quantum jumps. We remember in fact that, in the ordinary perspective of time t, quantum jumps are without duration, *ie* instantaneous. Section 3 reports the dynamic equations and is the main one. Section 4 underlines the conformity of the model to the consistency requirements posed by quantum cosmology intended in the standard sense. Final considerations are reported in Section 5.

2. Time and particles

2.1 Micro-universes and de Broglie oscillation

The first step is to identify a geometric representation of the de Broglie phase of an elementary particle that illustrates its connection with spacetime. For this purpose, let's imagine the usual spacetime as immersed in a five-dimensional environment-space in which also a maximally symmetrical micro-universe with a positive cosmological constant, of radius $c\theta \le c\theta_0$, is present. Here we denote with c the limit speed and with θ_0 a positive constant, having the dimensions of a time, the meaning of which we will return to later. This de Sitter micro-universe is tangent to spacetime at an event-point O corresponding to the spacetime position of the particle; for example the position of the center of charge of an electron [10,11]. Within the usual spacetime it is therefore possible, in the rest frame of reference of the electron, to represent O as $(\boldsymbol{x}, t)$, where t is the proper time of the electron. In general, however, the position $\boldsymbol{x}$ of the electron corresponding to a certain instant t is not definite; it is a fuzzy variable [12], whose statistical properties are defined by the spatial dependence of the electronic wave function. We assume that even the micro-universe integral with the electron center of charge is a quantum entity described by a wave function, solution of a suitable Wheeler-De Witt equation [13,14]. The square modulus of this wave function represents the probability of the state of the micro-universe.

The de Sitter quantum micro-universe is defined by a parameter which is its radius $c\theta \le c\theta_0$, where c is the maximum speed and θ is the so called de Sitter time [15], function of the type of particle; the maximum value θ_0 of θ defines a spatial scale of the micro-universes associated with elementary particles. We define the amplitude of probability of the *existence* of the micro-universe as $\psi = (\rho/\theta_0)\exp[\pm i(\varphi - \varphi_0)]$, where φ is the particle phase angle and ρ, with $0 \le \rho \le \theta_0$, has the dimensions of a time.

The de Broglie oscillation corresponds to the propagation in t of the particle when the state of the micro-universe associated with it is persistent, that is $\rho = \theta_0$ (the probability of existence is constant and unitary). In this circumstance $\psi = \exp[\pm i(\varphi(t)-\varphi_0)]$. For a free particle of renormalized mass m is $\varphi(t) = mc^2t/\hbar$ [1]; under a Lorentz transformation, the ψ function becomes a plane wave. According to the usual free wave equations (Schrödinger, Dirac, Klein-Gordon and so on), the particle wave function consists of a specific superposition of these plane waves, each of which represents the propagation of a persistent particle micro-universe in the absence of interactions. Another way of describing the situation is that the de Broglie oscillation corresponds to a solution of the Wheeler-De Witt equation in which the phase angle φ is chosen as the time variable.

If the micro-universe is not persistent, but evanescent, its probability of existence is not identically 1. In this case we can pose, without loss of generality, $\rho/\theta_0 = \exp(-|\tau|/\theta)$ and assume τ as a time variable. If the variation of ρ occurs for a constant value of φ and of t then it corresponds to a single instant in the domain of the laboratory time t; in the next Section 2.2 we will use this possibility to dynamically describe quantum jumps. In Section 3 we will see that both possibilities contemplated here (that is, persistent micro-universe and evanescent micro-universe) can be obtained with different choices of the time variable in the Wheeler-De Witt equation.

2.2 Micro-universes and quantum jumps

As is known, the temporal evolution of the de Broglie phase of a particle (and more generally of its wave function) undergoes a discontinuity in correspondence with an instantaneous elementary interaction event. This event, which sets the new initial condition of this evolution, is called a "quantum jump". The notion of quantum jump was first introduced by Bohr in his atomic model of 1913 [16], precisely in relation to the radiative processes involving an atomic electron. The quantum jump is therefore the definition of a value φ_0 starting from which the phase angle φ of the considered particle is measured. This is the value φ_0 which appears in the expression $\psi = \exp[\pm i(\varphi - \varphi_0)]$.

The propagation of the persistent micro-universe continues up to the phase angle φ_f at which the particle is involved in a new quantum jump; this jump determines the selection of a new angle φ_1 which replaces φ_0 in the expression of ψ. The same time instant t is associated both with φ_1 and φ_f; while the phase undergoes a jump determined by the difference $\varphi_1 - \varphi_f$. The succession of angles φ_0, φ_1, ... is specific to the history of the single particle, and this fact leads to the phenomenon of decoherence. Indeed, while the term ωt of the de Broglie oscillation remains unchanged to it is added, at the instant t of the jump, the phase variation $\Delta\varphi = \varphi_1 - \varphi_f$. Decoherence is induced by the fact that the succession of phase changes $\Delta\varphi$ to which the de Broglie oscillation undergoes, in concomitance with the successive quantum jumps to which the particle is subject, is specific to the single particle.

In a quantum jump, ρ undergoes a variation from θ_0 to 0 for φ fixed to φ_f, followed by a variation from 0 to θ_0 for φ fixed to φ_1. The first variation corresponds to the passage from a state having a probability of existence $(\rho/\theta_0)^2 = 1$ to another state having probability of existence $(\rho/\theta_0)^2 = 0$; we can consider it as the destruction of the state entering the quantum jump. The second variation corresponds to the transition from a state of probability $(\rho/\theta_0)^2 = 0$ to a state of probability $(\rho/\theta_0)^2 = 1$; we can consider it as the creation of a new initial state of the de Broglie phase factor. These two variations appear, in the domain of ordinary laboratory time, as limited to a single instant t with no duration. The two variations correspond to two "exponential tails" $\rho/\theta_0 = \exp(-|\tau|/\theta)$ at $\varphi = \varphi_f$, $\varphi = \varphi_1$ respectively. The first tail leads the particle micro-universe into a condition of "void", *ie* the absence of micro-universes. The second tail produces the particle micro-universe starting from this absence. Here we use the term "void", typical of the third quantization formalism, to distinguish this condition of absence from the more familiar "vacuum" of quantized fields spread over a space whose persistence is guaranteed [17]. The exponential tails associated with quantum jumps are clearly evanescent waves representing respectively the disappearance into the void of the micro-universe terminated by the quantum jump, and the appearance from the void of the micro-universe resetted in the quantum jump. The propagation of these waves does not occur in ordinary time t, but in unobservable "time" τ. These fading phenomena constitute the essence of what appears to us as *matter*. A micro-cosmological exploration of these phenomena was made in [18]. In the next Section 3 we give an independent derivation.

The two phase angles involved in a quantum jump, the final angle φ_f and the new initial angle φ_1, are connected by the passage through $\rho = 0$ and we have introduced the exponential tails as representations of this passage. But this same connection can be seen, in the variable φ, as a sort of tunneling which involves the passage across the intermediate angular values between φ_f and φ_1. Also this passage is, from the usual time perspective, enclosed in a single instant t which is that of the jump. However, we can think of assuming the phase angle (at constant t) as a dynamic variable identifiable in the cosmic time of a suitable micro-universe. This micro-universe is then a sort of wormhole that connects the two evanescent micro-universes associated with the tails.

The structure of a quantum jump can be described in the following way. Let's imagine a system of elementary particles described by the wave function Ψ which can be

decomposed, at a certain instant *t*, into the sum of two wave functions Φ and Ω according to $\Psi = \Phi + \Omega$. We also imagine that a single particle undergoes, at that very moment, a real (not virtual) interaction. The hypothesis is that the state of the particle leaving the interaction is represented in Φ, but not in Ω. In this case, the interaction induces a quantum jump that projects the function Ψ on the function Φ according to $\Psi \rightarrow \Phi$.

Before the jump, the particle "exists" as an element of the amplitude Φ contained in Ψ; after the jump, the particle "exists" as an element of the isolated amplitude Φ. The first version of the particle, the pre-jump one, is an oscillating de Broglie micro-universe that is terminated by an exponential tail; the second version of the particle, the post-jump one, is an oscillating de Broglie micro-universe that develops from an exponential tail; these two tails are connected by a wormhole in the terms indicated above. This representation does not apply to all the particles contained in Φ, but only to the one that has undergone the interaction. Since the actualization of this interaction involves a particle contained in Φ and not contained in Ω, the wave function Φ is actualized as an outgoing state from the projection. This projection selects the correlations between particles described in Φ, although these remain unexpressed. These correlations can also be non-local, as occurs in presence of entanglement. Non-interacting particles pre-existing in Φ are not altered in the projection process; therefore, the representation in terms of exponential tails and wormholes does not apply to them. The projection is induced by the single interaction undergone by a single particle.

In the case in which the particle undergoing the quantum jump is an elementary fermion of the Standard Model (lepton or quark), the corresponding wormhole represents the absorption or emission of the gauge boson that mediates the interaction (photon, $W^{\pm}$, Z^0, H^0, gluons or graviton). In principle, therefore, these wormholes are a description of the corpuscular aspects of gauge bosons. Finally, it must be noted that the quantum jump, considered in isolation, is time-symmetrical; if, in the previous discussion, we replace the single wave functions with their complex conjugates that propagate in the opposite direction of *t*, the wormhole is replaced by another identical wormhole that connects the same tails but with an inverted dynamic path.

2.3 Size of the micro-universe

Before continuing we focus on the relationship between the de Sitter time of a particle micro-universe and the mass *m* of the particle. The stabilization of the charges outgoing a quantum jump requires energy, because it is necessary to overcome the reaction of the vacuum of Dirac which otherwise would return to its ordinary state. To understand the topic, let's consider the particular case in which the outgoing state consists of a single electron. The negative charge of the positive energy electron repels the negative charges of the positive energy electrons that may be present, but attracts the negative charges of the negative energy electrons of the surrounding Dirac vacuum. At the same time, while the positrons with positive energy possibly present are attracted, the positrons with negative energy of the surrounding vacuum of Dirac are instead rejected. The first effect, i.e. the attraction of electrons with negative energy, increases the negative charge of the electron with positive energy; instead the second effect, that is the repulsion of the negative energy positrons, shields this charge. The total charge must naturally equal the charge of the electron with positive energy alone (renormalization of the charge) while the energy associated with the global deformation of the Dirac vacuum appears as the (finite) rest energy of the electron. This deformation induces a stable positive pressure which tends to bring Dirac's vacuum back to its undisturbed condition [19]. The hadronic case is more complex, in the sense that the hadron manifests itself as a bubble inside the gluonic condensate, which is completely opaque with respect to the propagation of the quarks. The latter are thus confined within the hadron. The pressure exerted by the condensate tends in this case to collapse the hadronic bubble, returning

the gluonic vacuum to its inperturbed condition [19]. In both cases, the Dirac vacuum pressure which tends to collapse the charges is balanced by the negative pressure induced by appropriate mechanisms which will be examined in Section 3.3. This balance gives rise to a de Sitter particle micro-space with mass density equal and opposite to the pressure. The renormalized values of charge and mass are related to this equilibrium.

Another way of expressing the same concept is the following. Let us imagine a particle micro-universe tangent to spacetime in O, which is the spacetime position of the center of charge of the particle. O sees the two sheets of de Sitter horizon, the past and the future, as placed at a chronological distance $\pm\theta$ (the de Sitter time of the micro-universe) and at a spatial distance $r = c\theta$. We can calculate the energy requested by the creation of the micro-universe as the energy needed to charge a capacitor to the level q_0 (renormalized charge) starting from the charge level 0. For an electronic micro-universe, this energy is:

$$\frac{q_0^2}{2C} \;=\; \frac{q_0^2}{2\,\varepsilon_0\,\dfrac{S}{d}} \;=\; \frac{q_0^2}{2\,\varepsilon_0\,\dfrac{4\pi r^2}{2r}} \;=\; \frac{q_0^2}{4\pi\varepsilon_0 r} \tag{1}$$

where the "vacuum capacity" C is expressed, temporarily using the units of the International System in order to make the concept clearer, in terms of the dielectric pemittivity of the vacuum ε_0. S is the 3-spatial surface of each of the two sheets of the de Sitter horizon and $d = 2r$ is the spacetime separation of the sheets. Substituting to q_0 the values e (elementary electric charge) in the case of charged leptons and $(\hbar c)^{1/2}$ in the case of hadrons (constant of strong coupling of hadrons in the hadrodynamical approximation [20]), the expression (1) must equal the rest energy of the particle. By restoring the usual units we have $mc^2 = e^2/c\theta$ for charged leptons and $mc^2 = \hbar c/c\theta$ for hadrons. Therefore, $r = c\theta$ coincides respectively with the classical radius of the charged lepton and with the Compton length of the hadron. The expression (1), of course, does not imply any notion of extended charge distribution. The maximum value θ_0 of θ thus remains experimentally identified (restricting our attention to only charged leptons and hadrons) as r_{cl}/c, where r_{cl} is the classical radius of the electron.

3. Third quantization

3.1 Micro-cosmology

In the previous Sections we have tried to clarify the physical aspects of our proposal. In this Section we focus instead on its formalization. A premise seems necessary to avoid possible misunderstandings. When we talk about cosmology in a non-quantum context, we usually take General Relativity as the reference theory. It is known that General Relativity is a theory of gravitation, even if in fact it should be said that it is a theory of gravitation and *inertia* (the two aspects are locally indistinguishable by virtue of the Principle of Equivalence, which constitutes the basis of theory). However, Einstein's equations are not just the gravity-inertia equations, but are the canonical equations that describe any conceivable coupling between matter-energy and spatial curvature that satisfies the general covariance criteria. They can therefore be used in a more general context, taking care to replace the gravitational constant appearing in them with a coupling constant pertinent to the case under investigation [6,7]. It is in this more general sense that we use them here to describe the particle micro-universes proposed in the previous Sections which, of course, are not governed by gravitation; what we instead propose in the following Section 3.3 is, accordingly to the Standard Model, a connection between the inertia of the particle (its proper mass) and a curvature associated with suitable scalar fields (Higgs).

Since we are dealing here with particles and therefore we are within the quantum realm, we actually consider the quantum version of Einstein's cosmological equations, namely the Wheeler-De Witt equation. This equation can be written in many forms. We start from the version proposed by Kiefer and collaborators [21], relating to a Friedmann universe with scale factor a and cosmological constant Λ, containing matter in the form of a scalar field ξ with potential $V(\xi)$:

$$\left[\frac{\hbar^2 \sigma^2}{12} \frac{\partial^2}{\partial \varepsilon^2} - \frac{\hbar^2}{2} \frac{\partial^2}{\partial \xi^2} + e^{6\varepsilon} \left(V(\xi) + \frac{\Lambda}{\sigma^2} \right) - 3e^{4\varepsilon} \frac{\kappa}{\sigma^2} \right] \Psi(\varepsilon, \xi) = 0 \qquad (2)$$

In Eq. (2) is $\varepsilon = \ln(a/a_0)$, where a_0 is the reference scale factor and κ is the curvature index of the spatial section of the universe: $\kappa = -1$ for a hyperbolic section, 0 for a flat section and 1 for a closed space. The symbol Ψ denotes the wave function of the universe, which expresses its amplitude of probability as a function of internal variables ε, ξ. σ is the coupling constant, which in the original theory is related to the Newtonian constant of gravitation G by the relation $\sigma^2 = 8\pi G$. As we said, our case is different and for it we have [18]:

$$\sigma^2 = \frac{12khc}{\left(Mc^2\right)^2} \qquad (3)$$

where M is the rest mass of the particle to which the micro-universe is associated and is $k = 1$ for hadrons, $k = \alpha$ (fine structure constant) for charged leptons.

Let's start by considering the case of evanescent micro-universes. The form taken by Eq. (2) in this particular case it is particularly simple. In fact, the evanescent micro-universes represent the restructuring of the vacuum caused by the temporal localization of the charges in a quantum jump (in the creation of the outgoing state), and the restoration of the original condition of the vacuum when the charges are removed (in the annihilation of the incoming state). We are therefore only interested in the conditions of a transient, evanescent universe in an empty environment, induced by a given final (respectively initial) condition. This means that in (2) we have to set $V = 0$ to cancel the pressure, $\kappa = 0$ to cancel the curvature and $\Lambda = 0$ to cancel the cosmological constant. With these positions (2) becomes:

$$\left(\frac{\sigma^2}{6} \frac{\partial^2}{\partial \varepsilon^2} - \frac{\partial^2}{\partial \xi^2} \right) \Psi(\varepsilon, \xi) = 0 \qquad (4)$$

In many quantum gravity applications it is customary to choose the units of measurement so that $\sigma^2 = 6$. We prefer first to multiply (4) by $6/\sigma^2$, then incorporate a factor $\sigma/6^{1/2}$ in ξ. With this choice ξ can be interpreted as a radius of curvature, consistent with what will be proposed in Section 3.3. In any case, a D'Alembert equation is obtained:

$$\left(\frac{\partial^2}{\partial \varepsilon^2} - \frac{\partial^2}{\partial \xi^2} \right) \Psi(\varepsilon, \xi) = 0 \qquad (5)$$

The Wheeler-De Witt equation does not contain time. This fact constitutes the origin of the well-known "problem of time" [21,22], on which we do not spread ourselves. But what if the quantity ε, which appears in (5) as a delocalized quantum variable, is taken as a time label? In this case it becomes an external parameter which, being dimensionless, can be written in the form $\varepsilon = \tau/\theta$, where the variable τ and the constant θ are time intervals. The scale factor then takes the form $a = a_0\exp(\tau/\theta)$. This is in fact the expression of the

scale distance in a de Sitter space with cosmic time τ and cosmological constant $\Lambda = 3/\theta^2$, solution of the Friedmann equation:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{\Lambda}{3} \tag{6}$$

in which the point denotes the derivation with respect to τ.

Let us now return to (5) and to the evanescence of the vacuum perturbation it describes. We look for separable solutions of the form $\Psi(\varepsilon,\xi) = \Phi(\varepsilon)\Gamma(\xi)$ that are evanescent. With simple calculations we obtain:

$$\Phi(\varepsilon) = \exp(-\varepsilon) = \exp\left(-\frac{\tau}{\theta}\right); \qquad \Gamma(\xi) = \exp\left(-\frac{\xi}{C\theta}\right) \tag{7}$$

where C is a constant that depends on the definition of ξ. The Eqs. (7) give a physical meaning to the parameter θ as an indicator of the rapidity of evanescence: comparing the evanescences associated with different particles, there will be more or less rapid ones depending on the corresponding value of θ. In this sense we can say that, in the specific case of the evanescent micro-universes treated here, these micro-universes are de Sitter spaces. The first equation (8) returns the exponential tails that we introduced "by hand" in Section 2, in relation to the passage from $\rho = \theta_0$ to $\rho = 0$ and viceversa.

However, (5) also admits separable harmonic solutions of the type:

$$\Phi(\varepsilon) = \exp(\pm ik\,\varepsilon) = \exp\left(\pm\frac{ikt}{\theta}\right) = \exp\left(\pm\frac{iMc^2 t}{\hbar}\right); \qquad \Gamma(\xi) = \exp(\pm ik\xi) \tag{8}$$

where $\varepsilon = t/\theta$; that is, the time variable is identified with the external time of the laboratory (proper time of the particle) and no longer as the internal time of the micro-universe. The k factor is the same as that which appears in (3). The first equation (8) is the usual de Broglie phase factor, associated with a persistent micro-universe.

A possible description of the wormhole-like micro-universe connecting the two tails in a quantum jump can be obtained by replacing, in Eqs. (7), τ/θ with $|\varphi|$, where φ is the phase angle and $\varphi \in [\min(\varphi_f, \varphi_1), \max(\varphi_f, \varphi_1)]$. Alternatively, the replacement $\tau/\theta \to i|\varphi|$ can be made in Eqs. (8), and we will return to this point later.

3.2 The context: connections between micro-universes

A quantum jump involving an elementary particle can therefore be seen as a pair of evanescent micro-universes connected by a third micro-universe. This aspect leads us to the multiverse and the formalism used to describe it: the third quantization formalism.

The third quantization formalism is a quantum field theory applied to a system of many universes in a superspace. We speak of "third quantization" because what is quantized is the wave function of the universe, and this in turn depends on the material fields within that universe, which have already been subjected to the second quantization. The starting point is the Wheeler-De Witt equation. One of the variables on which the wave function, solution of the equation, depends is assumed as a time variable and on this basis the same procedure used in the second quantization is applied. This approach is applied to quantum cosmology problems related to the tunneling of universes and the nucleation and reabsorption of baby universes within a parent universe. We will not describe it here in general terms, referring the reader to the relevant bibliography [17,23,24]; instead we will try to summarize the main ideas by taking as an example a particular case close to our topic.

We therefore consider a Friedmann-Robertson-Lemaitre-Walker space with closed spatial sections, filled with a homogeneous and isotropic fluid whose pressure is p and whose density is η, these quantities being connected by the equation of state $p = w\eta$ (we use here units $c = 1$). In addition is assumed the presence of a massless scalar field ξ. The relevant Wheeler-De Witt equation can be written in the form [25]:

$$\left(a^2 \frac{\partial^2}{\partial a^2} + a \frac{\partial}{\partial a} + \frac{\omega_0^2 a^{2q} - a^4}{\hbar^2} - \frac{\partial^2}{\partial \xi^2} \right) \Psi(a,\xi) = 0 \tag{9}$$

where a is the scale factor and ω_0 is an integration constant dependent on the energy density on a defined hyper-surface Σ. The parameter $q = 3(1 - w)/2$ defines the matter scheme: radiation for $w = 1/3$, dust for $w = 0$ and pure cosmological constant for $w = -1$. Assuming the latter case, we have $q = 3$ and $\omega_0^2 = \Lambda$. Therefore, the Eq. (9) becomes:

$$\left[\hbar^2 \frac{\partial^2}{\partial a^2} + \frac{\hbar^2}{a} \frac{\partial}{\partial a} - \frac{\hbar^2}{a^2} \frac{\partial^2}{\partial \xi^2} + \left(\Lambda a^4 - a^2 \right) \right] \Psi(a,\xi) = 0 \tag{10}$$

At this point the wave function Ψ is promoted to operator [17], and the possibility of its decomposition in normal modes is admitted:

$$\hat{\Psi}(a,\xi) = \int dk \, [e^{ik\xi} A_k(a) \hat{c}_k^+ + e^{-ik\xi} A_k^* \hat{c}_k] \tag{11}$$

The amplitudes A_k then satisfy the equation of the damped harmonic oscillator:

$$\left(\hbar^2 \frac{\partial^2}{\partial a^2} + \frac{\hbar^2}{a} \frac{\partial}{\partial a} + \omega_k^2(a) \right) A_k(a) = 0 \tag{12}$$

where:

$$\omega_k(a) = \sqrt{ \Lambda a^4 - a^2 + \frac{\hbar^2 k^2}{a^2} } \tag{13}$$

The creation and annihilation operators of mode k of the universe are expressed by:

$$\hat{c}^+ = \sqrt{\frac{\omega_{0k}}{2\hbar}} \left(\hat{\Psi} - \frac{i}{\omega_{0k}} \hat{p}_\Psi \right) ; \qquad \hat{c} = \sqrt{\frac{\omega_{0k}}{2\hbar}} \left(\hat{\Psi} + \frac{i}{\omega_{0k}} \hat{p}_\Psi \right) \tag{14}$$

where ω_{0k} is the value derived from (14) on Σ. It should be noted that the values of $\omega_k(a)$ given by (13) can be as well as real than complex. The transition from the real to the complex domain represents the transition from the Lorentzian to the Euclidean region of the universe. For example, in the case $k = 0$ one has a de Sitter space for $a > \Lambda^{-1/2}$, while for $a < \Lambda^{-1/2}$ one has a de Sitter instanton collapsing on Euclidean time.

An essential point is that having defined the creation and annihilation operators, it is possible to connect a state of the universe to the void in the same way that, in second quantization, a state of the field is connected to the vacuum [17]:

$$\left| \hat{\Psi}(a) \right\rangle = \prod_k e^{v_k c_k^+ - v_k^* c_k} \left| 0 \right\rangle_k \tag{15}$$

An expression such as (15) can describe, for example, the creation of pairs of universes or their annihilation, the merging of universes or the stemming of universes from parent universes and other processes quite similar to those known in elementary particle physics [17]. However, while these concepts are usually applied to the study of quantum cosmology and therefore to situations in which, roughly speaking, the universe is "small" and behaves like a particle, we ask ourselves instead whether, on the contrary, particles can not be described as micro-universes. In fact, it seems to us that this language is adequate for a non-singular description of the particles and quantum jumps in which they are involved.

3.3 If not gravitation, what else? A hypothesis on the Higgs mechanism

The curvature of the particle micro-universe can be expressed as the product of a constant, dependent on the particle (hadronic state or single quark or lepton), for a universal curvature. The constant is the coupling factor of that particle to this curvature. The universal curvature can be connected to the expectation value in vacuum of a suitable scalar field: the field of sigma models in the hadronic case [26,27], the Higgs field in the case of elementary fermions of the Standard Model. Here we limit ourselves to considering the Higgs field, referring the reader to the works of other authors for the discussion of the hadronic case [28,29]. However, the line of reasoning is the same in both cases.

The Higgs field is introduced in the usual way, as an iso-doublet Ω of scalar fields defined on the space SU(2) of the weak isospin. The fields will depend on the spacetime position. We denote by ε (having the dimensions of an energy) the expectation value of the vacuum (VEV), defined in the usual way. Let's consider the energy f defined by the relation:

$$\left|\Omega\right|^2 \,=\, \Omega^+\Omega \,=\, \varepsilon f \tag{16}$$

The symmetry breaking, that is the passage from $f = 0$ (the "false vacuum") to $f = \varepsilon$ (the "true vacuum"), corresponds in the SU(2) space to the choice of a specific direction of the spinor Ω of norm ε as the new vacuum state. $|\Omega| = \varepsilon$ must be a stable point of the potential of the free Higgs field. This potential must be even in $\varepsilon(f - \varepsilon)$ and then be expressed by a sum of even powers of $(|\Omega|^2 - \varepsilon^2)$. The only possibility compatible with renormalization is that of a completely harmonic dynamics of the variable $\varepsilon(f - \varepsilon)$, in accordance with the usual choice of a potential proportional to $\varepsilon^2(f - \varepsilon)^2$, that is $(|\Omega|^2 - \varepsilon^2)^2$.

It is possible to associate the Higgs field to a de Sitter space whose curvature is the universal curvature $-R_0$, rewriting its internal potential in the form [30]:

$$V(\Omega) \,=\, \frac{\sqrt{Det(g_{\mu\nu})}}{4\pi}\left[\frac{R_0}{6}\Omega^+\Omega - \frac{\chi_0 R_0}{36}\left(\Omega^+\Omega\right)^2\right] \tag{17}$$

where the determinant of the metric matrix of the de Sitter space appears and we pose:

$$R_0 \,=\, 6\mu^2 \tag{18}$$

while χ_0 is the internal "gravitational constant" of the Higgs micro-universe.

The relationship between the value of the vacuum expectation ε and the rest mass M_W of the W boson is that predicted by the conventional mechanism:

$$\varepsilon = \frac{\sqrt{2}\,c^2}{g} M_W \tag{19}$$

where g represents the electroweak coupling constant. Expanding around ε in the usual way we then have:

$$\varepsilon = c^2 \left(\frac{3}{\chi_0}\right)^{1/2} \quad\Rightarrow\quad \chi_0 = \frac{3}{2}\frac{g^2}{M_W^2} \tag{20}$$

$$M_H = \frac{\hbar}{c}\left(-\frac{R_0}{3}\right)^{1/2} \quad\Rightarrow\quad R_0 = -\frac{3M_H^2 c^2}{\hbar^2} \tag{21}$$

$$V(\Omega) = \mu^2\,\Omega^+\Omega + \lambda\left(\Omega^+\Omega\right)^2 \tag{22}$$

where $\lambda = -\chi_0 R_0/36$, M_H is the Higgs boson mass and:

$$\mu^2 = -\frac{1}{2}\frac{M_H^2 c^2}{\hbar^2} \tag{23}$$

The existence of a de Sitter space associated with the Higgs field in accordance with (17)-(23) represents our specific hypothesis relating to the Higgs field. On the other hand, it is known from the Standard Model that the mass of an elementary fermion (quark or lepton) is given by the product of ε for a specific coupling constant of that fermion. As can be seen from (20), this is equivalent to rescaling the gravitational constant, which passes from the value χ_0 to a new value χ specific to the fermion.

If V is the volume of the projection, on the Minkowski spacetime, of the new de Sitter space associated with the fermion and p is the pressure within this space, the rest mass M must satisfy the relation $pdV = c^2 dM$. Based on what has been previously argued, an increase of V must result in a decrease of M; this is congruent with a negative p. Therefore $dM/dV = -\eta$, where η is the matter density inside the horizon; that is $p + \eta c^2 = 0$.

The micro-space of scalar curvature R and cosmological constant Λ_0 satisfies the Einstein equations:

$$R_{\mu\nu} - \frac{R}{2}g_{\mu\nu} + \Lambda_0 g_{\mu\nu} = \chi T_{\mu\nu} \tag{24}$$

where $\mu, \nu = 0,1,2,3$ and the symbols have the usual meaning. Here the metric tensor $g_{\mu\nu}$ is that experienced by the centers of charge within the particle, while Einstein's "gravitational" constant χ actually measures the coupling with the VEV. By schematizing the internal vacuum as a perfect fluid, the stress tensor takes the form:

$$T_{\mu\nu} = \left(\eta + \frac{p}{c^2}\right)u_\mu u_\nu + p g_{\mu\nu} \tag{25}$$

where the four-velocity field of matter $u_{\mu\nu}$ is introduced. Since $p + \eta c^2 = 0$, the (24) becomes:

$$R_{\mu\nu} - \frac{R}{2}g_{\mu\nu} + (\Lambda_0 + \chi\eta c^2)g_{\mu\nu} = 0 \tag{26}$$

which is the equation of a de Sitter space with an "effective" cosmological constant $\Lambda = \Lambda_0 + \chi\eta c^2$. Neglecting the native (cosmological) constant Λ_0, we have $\Lambda = \chi\eta c^2 = R/4$. The χ rescaling therefore coincides with a rescaling of R_0 in R.

In other words, Eq. (20) provides an expression for the expectation value ε of the Higgs field in the vacuum where the "gravitational" constant χ_0 of the micro-universe corresponding to this vacuum appears. The Standard Model defines the mass M of a particle as the product of ε by a suitable dimensionless coupling constant dependent on the particle. In terms of the present model, this implies the rescaling $\varepsilon \rightarrow f\varepsilon$ where:

$$f\varepsilon = c^2 \left(\frac{3}{\chi} \right)^{1/2} \tag{27}$$

This rescaling leads to a new micro-universe (that of the particle) with a "gravitational" constant χ. From Eqs. (20), (27) we have:

$$f^2 = \frac{3}{\chi} \frac{\chi_0}{3} = \frac{\chi_0}{\chi} \tag{28}$$

From the relation $\Lambda = \chi\eta c^2$ between the cosmological constant Λ of the new micro-universe, its mass density η and the "gravitational" constant χ we obtain:

$$\frac{1}{\chi} \propto \frac{\eta c^2}{\Lambda} \propto M^{-2} \frac{M}{(M^{-1})^3} = M^2 \tag{29}$$

since $\Lambda = 3/(c\theta)^2$ and $c\theta$ is inversely proportional to M. This result conforms to Eq. (3). We therefore have:

$$f^2 \propto \frac{1}{\chi} \propto M^2 \tag{30}$$

That is $M \propto f$, according to the conventional Higgs mechanism and the Standard Model.

3.4 Open questions and experimental control

One question that remains open is the kind of the micro-universe that connects the two evanescent tails, that is, whether it is described by an evanescent amplitude $\Phi = \exp(-|\varphi|)$ or by a harmonic amplitude $\Phi = \exp(\pm i|\varphi|)$. In the first case we have an evanescent micro-universe (Euclidean time), in the second a persistent micro-universe (Lorentzian time). In both cases the existence of such a micro-universe is reduced, in the temporal domain t in which we operate, to a single instant. The first possibility prefers smaller phase jumps, while the second makes all phase variations $\Delta\varphi$ equally probable. The latter possibility is the one normally considered since the early days of quantum mechanics (see for example Heisenberg [31]).

A direct experimental control would consist in measuring the phase of the wave function before and after the quantum jump, and in determining the difference $\Delta\varphi$ of the two phases. By constructing a frequency histogram of the various values of the modulus of this difference, one could go back to the correct determination of the probability $P(|\Delta\varphi|)$. However, such an approach is impossible, because notoriously the global phase of a wave function is not measurable. Even more: the wave function is defined up to a global phase, so such a proposal has no logical basis.

It is therefore necessary to approach the problem indirectly. Let us imagine to send a beam of bosonic particles, perfectly coherent in phase, on a medium where they undergo quantum jumps through interactions with microscopic components of the medium itself. It is evident that in the evanescent case decoherence occurs more slowly than in the "Lorentzian" case, because smaller phase jumps are preferred. Therefore it will take more jumps to obtain the same degree of decoherence obtainable in the alternative "Lorentzian" case. From a theoretical point of view, the degree of decoherence can be estimated, if Φ is known, by averaging on the histories of single particles. Or, for example, by studying the behaviour of the off-diagonal terms of the density matrix after repeated quantum jumps. The theoretical prediction of the evolution of decoherence as a function of the number of interactions can then be compared with the experimental result. We do not develop here the relative considerations, which would require a separate paper, but what is interesting, even beyond the case in point, is that such a methodology provides experimental indications on Φ and therefore, from our point of view, on the nature of intermediate universe. The relevant point here is that if our argument is correct, the hypothesized internal dynamics of a quantum jump is - at least partially - experimentally investigable.

4. Cosmological implications

The authors of an interesting paper [32] ask themselves what may be, at a cosmological level, the cause of the breaking of the homogeneity and isotropy of the distribution of matter in the phases of cosmic evolution immediately following the end of the inflationary era. In fact, it is generally believed that the "quantum fluctuations" originating during inflation are the seeds from which density inhomogeneities develop. The subsequent amplification of these inhomogeneities caused by gravitation leads to the emergence of structures, such as clusters and galaxies and, within the latter, stars and planets. The important point is that while amplification processes are essentially classical, in the sense that quantum aspects do not seem to play a significant role in them, the origination of seeds is due to the conversion of quantum fluctuations and therefore falls within the realm of quantum processes. The quantum fields that govern the inflationary era notoriously represent possibilities: the possibility of events. What leads to the formation of seeds is the actualization of these possibilities in concrete inhomogeneities of density over spacetime. The problem is therefore the same as that which arises in the description of quantum measurement: understanding how the selection of an outgoing microscopic state takes place which is the true result of the measurement, followed by its amplification at macroscopic levels and its registration by irreversible processes.

It is known that this problem admits no solution in the conventional formulation of quantum theory. The latter is in fact agnostic with respect to the definition of the nature of the collapse of the wave function, its causes, and the level at which it occurs. On this point the "interpretations" of this formulation abound. The authors carry out an examination of all the main classes of interpretations and conclude that none of them is able to give an answer to the cosmological problem proposed. This conclusion is obvious for those interpretations that attribute the cause of the collapse to the observer, or to observation processes, because no observer or classical observation apparatus is available at the end of the inflationary era! For more subtle but equally fundamental reasons, for which we refer to the original work [32], neither modal scenarios or those based on decoherence caused by the environment, nor relative state approaches are able to solve the problem. The point is that the description of the problem, in the usual context of measurement, provided by these approaches presupposes an asymmetry (for example in the environmental degrees of freedom) that is simply lacking in the perfect homogeneity

present at the end of the inflationary flattening. The enigma is precisely the origin of the asymmetry.

The authors note that the context that originates the problem can also be transferred to the current Universe, and in this regard they reconsider a simple conceptual experiment analyzed in 1929 by Mott [33]. This is an idealized experiment, which represents a first attempt of a measurement theory applied to the explanation of the tracks caused by the passage of alpha particles in a cloud chamber. An alpha-emitting nucleus, placed between two hydrogen atoms arranged in a straight line with it, is considered. The nucleus emits the alpha particle in a spherically symmetrical state and the interaction Hamiltonian between the alpha particle and the electrons of the two hydrogen atoms is spherically symmetrical; one wonders what determines the breaking of this symmetry and the formation (on a local scale) of the track. Mott's solution is that the excitation of atomic electrons is spatially localized and this is what breaks the spherical symmetry. But this explanation assumes an initial asymmetry: the hydrogen atoms are placed there since the begin. What would happen if they too were in a spherically symmetrical state around the emission point of the alpha particle? In this case it is easily demonstrated that the unitary evolution of the global quantum state maintains this symmetry, which can therefore only be broken by a collapse of the wave function. Navigating backwards, this explanation can also be applied to the analogous cosmological problem, with the additional condition that the collapse cannot originate from observations. The quantum jump is a collapse of an objective nature, originating entirely from fundamental interactions. It is therefore the solution of the problem, as indicated by the authors [32], and we take up this suggestion.

In fact, we propose a dynamical model of quantum jump, which is considered since the begin as a process of spacetime localization of physical quantities: an exact localization in a temporal sense, partial in a spatial sense. Spatially, in fact, the quantities remain delocalized according to the outgoing wave function. If we consider the experiment proposed by Mott in its variant in which even the hydrogen atoms are spherically distributed, it is the quantum jump associated with the interaction between the alpha particle and the electron that breaks the spherical symmetry of the wave function Ψ. We can indeed decompose Ψ in the sum of a wave function Φ which describes all the evolutionary possibilities in which there is an excitation of the atomic electron of one of the two atoms in a definite space region, and of a wave function Ω which describes all the evolutionary possibilities in which the excitation of the electron of that specific atom in that region is not present. The wormhole that connects the electron present in the pre-jump Φ with the same electron present in the post-jump Φ induces the projection $\Psi \rightarrow \Phi$, which selects the evolutionary possibilities conditioned by the actualization of the electron excitation in that region. The wormhole has a precise time location, as it is instantaneous in the domain of the laboratory time t. Moreover, it has a spatial delocalization which is that of the excited electron. The excitation event is approximately delocalized according to the orbital of the specific hydrogen atom considered, whose centroid provides approximately the position of the nucleus of that atom, which is then also selected in the jump. The spherical symmetry of the initial state is thus lost. The explanation of the analogous cosmological problem is certainly more complex, and we will not attempt one here. What we are interested in underlining is that an event-based approach to quantum theory such as the one proposed here seems to make possible the application of quantum formalism also to the cosmological context, allowing an understanding of the breaking of the original symmetries and of the nucleation of the seeds of the structures.

5.   Conclusions

The interpretations of the quantum formalism can be classified on the basis of their consideration of the projection postulate, and therefore of the collapse of the wave func-

tion. For many of these interpretations it remains an anomalous postulate, which one tries to eliminate through the elucidation of mechanisms that restore an absolute unitarity of the theory. Here we assume instead a framework in which collapse is a genuine *physical* phenomenon of breaking of unitarity, attributable to the interactions of the Standard Model. It thus bridges the foundational aspects of the "quantum" and the modern physics of particles and fields.

To this aim, the old quantum jump introduced, at the dawn of quantum mechanics, in the description of radiative processes is revisited. The collapse is identified with the quantum jump and therefore with a physical phenomenon induced by an interaction (even negative) between elementary particles of the Standard Model. This choice distinguishes the present scenario from other proposals not yet substantiated experimentally, such as spontaneous localization models, according to which collapse remains a distinct phenomenon induced by exotic interactions with the vacuum.

The formal description adopted for the quantum jump is that of a discontinuity in the time evolution of the monochromatic components of the wave function (de Broglie phase waves). This discontinuity is described as the localization, in the usual time domain, of the particle center of charge. It is assumed that the deformation of the vacuum resulting from this localization leads to the formation of a micro-space with constant positive curvature, tangent to spacetime. It therefore becomes possible to apply the language of the third quantization to the description of the quantum jump.

The third quantization was developed in the late 1980s to study the fluctuations of space-time, and proved to be a very powerful and clear framework describing the multiverse and various aspects of its conceptual constellations such as virtual black holes, wormholes and baby universes [34 -37]. It develops from the Wheeler-de Witt equation (WdW), in which the time variable is not fixed a priori; the possible solutions are therefore incomputable [38]. The choice of the time variable thus implies the selection of an evolutionary mechanism. The quantum jump represents the non-unitary aspect of the interaction of the Standard Model that induces it (*eg* the electromagnetic interaction between electron and photon in quantum jumps of atomic electrons), and consists in a selection of the de Broglie phase in the "multiverse" of possibilities previously existing, which is accompanied by the localization of the particle over time. The decoherence is thus generated by the "common" interaction processes and in this context the possibility of geometrically describing the breakdown of unitarity through the action of a wormhole is considered.

The well known approach of multiverse and particle-like universes [39-41] is used here by replacing gravitation with scalar fields, such as that of Higgs, which size the particle micro-universe. The particle, in its "corpuscular" aspect, is seen as an event rather than an object. In this sense, no ontological role of a classical type is assigned to the particle micro-universe, unlike previous similar theoretical elaborations [5]. The investigation into the nature of the "collapse", which remained among epistemological speculations for a long time, thus blends naturally with particle physics to the point of suggesting a relationship between the Higgs mechanism and localization.

This "event based" perspective of elementary processes finally offers simple mechanisms (discussed in Section 4) for breaking the homogeneity of the distribution of matter at the end of the inflationary era and for generating the seeds of structures destined to evolve into galaxies and clusters. This perspective, although used here in a "micro-cosmological" context linked to elementary particles, may perhaps constitute a language that can be exported to the same quantum cosmology understood in the conventional sense, as recent suggestions seem to indicate [42-45].

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