

Article

Event-Based Quantum Mechanics: A Context for the Emergence of Classical Information

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Abstract: This paper explores an event-based version of quantum mechanics which differs from the commonly accepted one, even though the usual elements of quantum formalism, e.g., the Hilbert space, are maintained. This version introduces as primary element the occurrence of micro-events induced by usual physical (mechanical, electromagnetic and so on) interactions. These micro-events correspond to state reductions and are identified with quantum jumps, already introduced by Bohr in his atomic model and experimentally well established today. Macroscopic bodies are defined as clusters of jumps; the emergence of classicality thus becomes understandable and time honoured paradoxes can be solved. In particular, we discuss the cat paradox in this context. Quantum jumps are described as temporal localizations of physical quantities; if the information associated with these localizations has to be finite, two time scales spontaneously appear: an upper cosmological scale and a lower scale of elementary “particles”. This allows the interpretation of the Bekenstein limit like a particular informational constraint on the manifestation of a micro-event in the cosmos it belongs. The topic appears relevant in relation to recent discussions on possible spatiotemporal constraints on quantum computing.

Keywords: Bekenstein information; emergent time; localization; quantum jump; quantum measurements

1. Introduction

Quantum mechanics (QM) is the current theory of reference in the study of the micro-physical world. The application of its principles led to the full elucidation of the behavior of matter at the particle scale, of the atomic nuclei, of atoms, of molecules, of condensed matter. Such principles are at the base of the prodigious development of today’s quantum technologies. In addition, it was the starting point for the formulation of quantum field theory. Nevertheless, the nature of the physical world at the scale of quantum processes remains the subject of debate [1]. In particular, the mechanisms that convert the quantum information associated with these processes into classical information, thus allowing the emergence of the macroscopic classical world, remain elusive. In this article we wish to investigate these mechanisms in a new light. In order to illustrate the approach, let us consider an unstable microscopic quantum system, let us say an atomic nucleus of Radium 226 in isolation. This system decays in Radon 222 with a very long half-life (1600 years); this means that the nuclear

quantum amplitude undergoes a slow unitary time evolution tending asymptotically to the amplitude of the nuclear state designated as Radon 222. This description would potentially be applicable both to the single nucleus of Radium 226 and to a set of nuclei of Radium 226 prepared at the same initial moment. Now, the peculiarity of QM is that the amplitude of a single nucleus of Radium 226 can undergo a discontinuous jump to the amplitude representative of the Radon 222. This discontinuous evolution is what is called a quantum jump (QJ).

It is noteworthy, first of all, that a QJ is an event in the history of a single nucleus; identical nuclei simultaneously prepared in the same way will decay at different times. Therefore, the time evolution of the set of all these nuclei will lead to a mixture consisting of a decreasing fraction of non-decayed nuclei (whose amplitudes will be expressed by the same superposition of Radium 226 and Radon 222) and a growing fraction of Radon 222. Moreover the decay, that is the QJ, is an objective physical fact. Indeed a detector placed near the nucleus that undergoes the decay will detect an alpha particle, product of the decay (and possibly the gamma photon of rearrangement). By applying the principles of conservation of physical quantities such as charge, energy and impulse, we obtain that the quantities transported by the decay products are those related to the transformation of Radium 226 in Radon 222. Since the emission of these products is instantaneous with respect to the unitary evolution of the nuclear amplitude, it follows that the QJ is instantaneous on the scale of this second process (and it can be assumed that it is instantaneous in the strict sense).

Therefore, there is an objective physical process, the QJ, which converts quantum information, associated with a superposition, in classical information associated with a mixture. This process operates on a microscopic scale, therefore in the absence of any noise that can produce decoherence and in total isolation. Furthermore, it does not depend on the presence or absence of measurement devices (which can reveal at most the decay products when the process has ended). The QJ is clearly an outcome of the known and usual physical interactions: specifically, the strong nuclear interaction governing the alpha decay. These interactions produce two effects: a unitary evolution of the amplitudes that can be described in principle by the quantum equations of motion and their discontinuous and non-unitary variation constituted by the QJ. In other words, each interaction induces both Hamiltonian and non-Hamiltonian effects on the evolution of quantum amplitudes. The quantum jumps were introduced by Bohr in his famous trilogy [2–4], in relation to the explanation of atomic spectral lines. Direct observation of atomic QJs and their discrimination from the underlying unitary process required the development of refined experimental methods that became available in the mid 1980s. With the method of ionic traps was possible to use “shelved” atoms for this observation [5]. Subsequently, quantum jumps were directly observed in a number of atomic, molecular, electromagnetic and nuclear microsystems [6–19].

However, while the QJs represent a well established experimental fact, the current formulations of the QM are not based on the explicit recognition of their existence. It is good to repeat that QJ is a real physical phenomenon (for example, the effective transmutation of an atomic nucleus with the emission of observable decay products) that occurs as the effect of a specific interaction (in the example, a strong interaction). It should not be confused with its effect, i.e., the reduction of quantum amplitude and the consequent production of classical information. Furthermore, while this information may become available as a measure of the knowledge acquired by a human observer, the presence of such an observer is not a necessary condition for the QJ to take place. We take the QJs as elementary “events” of an objective physical world, independent of the presence of observers. Furthermore, we adopt an ontological perspective where the macroscopic systems are stable aspects of recurrent schemes of QJs. The QM, reformulated according to these principles, thus becomes a description of the physics of this objective world. Now we want to discuss some of the advantages of this perspective.

Since the QJs induce a reduction of quantum amplitude, one may question if they may have some relationship with the other phenomenon to which the QM attributes the same property, that is, the measurement. In this paper we will assume that the reduction induced by the quantum measurement process is nothing but the effect of a quantum jump on the evolution of the complex consisting of the

79 measurement apparatus and the micro-entity. For consistency with the previous reasoning, the jump
80 will be the non-Hamiltonian effect of the (even negative) interaction between the apparatus and the
81 micro-entity. In this way the measurement becomes an ordinary physical phenomenon and we can
82 consider it as a special case of QJ. The concepts of “measurement” and “observable” therefore lose
83 their centrality in the construction of the theory. The peculiarities of quantum measurement will be
84 examined later.

85 The succession of the QJs experienced over time by the same elementary “quantum system” is
86 naturally a discrete set: two successive QJs are separated by a finite time interval. The lack of existence
87 of events related to the system in this interval means that in this interval the “system”, intended as
88 a set of QJs, does not exist in time. The elementary “quantum system” is therefore not an object, in
89 the classical sense: it is a causal connection between single QJs. Its identity will be characterized by
90 the existence of a specific Hilbert space where the transition amplitude between a QJ and the next is
91 evaluated (if the number of particles is not conserved, we will have instead a Fock space, but in this
92 paper we will not discuss this circumstance). The quantum amplitude (bra or ket) associated with a
93 system is therefore not the “state” of some object; in particular, a superposition of amplitudes should
94 not be intended as a superposition of “states”. The situation is very different if the “quantum system”
95 is not elementary, that is, it consists of a multiplicity of elementary constituents able to interact between
96 themselves with production of many QJs at the same time. The characterization of the system will
97 then also require the specification of these QJs. The case of classical macro-systems is that of the ideal
98 limit in which the system is defined entirely by average properties, relatively stable over time, of an
99 enormously high number of QJs. Such a system is an object, it is endowed with continuous existence
100 in time and its state is described by classical variables, to which classical measures of information
101 are attributable.

102 By attributing the role of primary constituents of the physical world on the quantum scale
103 to the QJs is therefore possible to construct a version of the QM in which the transition from the
104 (fundamental) quantum level to the classical one is fully understandable. To construct such a version
105 we have to remember that a QJ projects the quantum amplitude of the system on a given subspace of
106 the Hilbert space; it can therefore be represented by a self-conjugated operator. The QJ is therefore the
107 localization, in the temporal domain, of that projection and of the physical quantities associated with
108 it. Temporal localizations of physical quantities thus assume the role of primary elements of physical
109 reality, with the result that this one is made up of events, and no longer objects.

110 This formulation assigns the same theoretical and experimental significance to two inseparable
111 and complementary aspects of the quantum world: that localized in time (QJs) and that not localized
112 in time (amplitudes). The relationship between these two aspects can be described in terms of the
113 relationship between quantum information coded in the Hilbert space and classical information
114 produced in the QJs. In particular, the Bekenstein limit becomes a limit on classical information which
115 can be expressed in a finite volume of space by the QJs. If this limit has to be finite, the temporal
116 de-localization must be limited both above, on the cosmological scale, and below. This last constraint
117 determines the appearance of a scale of elementary particles, an element which is not explicit in the
118 usual formulation of the QM. The evolution of the superposition of amplitudes in a quantum computer,
119 however, does not happen in spacetime. Therefore, this evolution does not seem to be limited by
120 spatio-temporal constraints, which instead can afflict the input-output operations. The recent debate on
121 the possibilities of quantum computing raised by Davies and Aaronson [20,21] should be considered
122 in this perspective.

123 The structure of this paper is as follows. In Section 2, the quantum basic notions are re-arranged
124 according to the principles outlined in this introduction; in particular the notion of event is specified
125 and the Born rule is introduced. Section 3 briefly introduces the notions of classical system and
126 measurement. Section 4 is dedicated to the discussion of the cat paradox. In Section 5 we discuss the
127 relationship between localization and information. In Section 6, some considerations about the possible
128 spatiotemporal limits of quantum computing are discussed according to the perspective illustrated

129 in this paper. A comparison with other similar approaches in the literature is reported in Section 7.
130 Open problems and the possibility of future research are briefly sketched in Conclusions.

131 2. Rewriting Quantum Postulates

132 In this section we present a reformulation of the basic concepts of the QM according to the
133 recognition of the fundamental nature of the QJs as events on the quantum scale. In order to highlight
134 the impact of this recognition, we will refer to the semi-formalized presentation level typical of
135 textbooks. In our intervention on the standard formalism we will try to be as conservative as possible,
136 compatibly with the variations we intend to represent.

137 We assume two primitive theoretical concepts:

- 138 1) A real variable $t \in T \subset \mathbb{R}$, the 'time'.
139 2) A 'rigged' Hilbert space \mathbf{H} with a scalar product $\langle \varphi | \psi \rangle \in \mathbb{C}; |\psi\rangle, |\varphi\rangle \in \mathbf{H}$.

140 Postulate 1. $\exists E \subset T$ such that:

- 141 a) E is finite or countable;
142 b) $\forall t_k \in E, k \in \mathbb{N}, \exists! f : t_k \rightarrow |\psi_{t_k}\rangle\langle\psi_{t_k}|; |\psi_{t_k}\rangle \in \mathbf{H}$
143 c) For each value of k , a conditional probability $Prob[(|\psi_{t_k}\rangle\langle\psi_{t_k}|) \parallel (|\psi_{t_{k+1}}\rangle\langle\psi_{t_{k+1}}|)] =$
144 $Prob[(|\psi_{t_{k+1}}\rangle\langle\psi_{t_{k+1}}|) \parallel (|\psi_{t_k}\rangle\langle\psi_{t_k}|)]$ exists.

We call the application f the 'manifestation' of the 'event' $|\psi_{t_k}\rangle\langle\psi_{t_k}|$. As one can see, this event is a self-adjoint operator on \mathbf{H} ; t_k is the 'instant' when the event 'occurs'. It is assumed that $t_{k+1} \geq t_k$, $\forall k \in \mathbb{N}$ and there are not events manifested in the interval (t_k, t_{k+1}) . The postulate 1 thus defines a causal structure of successive events based on a conditional probability. Let us consider now a linear operator \hat{o} on \mathbf{H} , which is diagonal in the orthonormed and complete basis $|\phi_i\rangle; i = 1, 2, 3, \dots$:

$$\hat{o} = \sum_i o_i |\phi_i\rangle\langle\phi_i| \quad (1)$$

145 The projector $|\phi_i\rangle\langle\phi_i|$ is a possible image of the application f at the time t if $\exists |\psi\rangle \in \mathbf{H}$ such that
146 $Prob[(|\psi_{t'}\rangle\langle\psi_{t'}|) \parallel (|\phi_{i,t}\rangle\langle\phi_{i,t}|)] \neq 0$, where $t' \in T$. If $o_i \in \mathbb{R}$ and each $|\phi_i\rangle\langle\phi_i|$ is a possible image of the
147 application f then \hat{o} is called 'physical quantity' on the space \mathbf{H} .

Postulate 2. The conditional probability of two successive events $|\psi_{t_k}\rangle\langle\psi_{t_k}|$ and $|\psi_{t_{k+1}}\rangle\langle\psi_{t_{k+1}}|$ is expressed as:

$$P = \langle\psi_{t_{k+1}}|\hat{S}|\psi_{t_k}\rangle\langle\psi_{t_k}|\hat{S}|\psi_{t_{k+1}}\rangle \quad (2)$$

with

$$\hat{S} = \exp\left(-\frac{i}{\hbar} \int_{t_k}^t \hat{H} d\sigma\right); \sigma \in (t_k, t_{k+1}) \quad (3)$$

148 where $\hat{H} = \hat{H}^+$ is a physical quantity on \mathbf{H} called 'Hamiltonian'.

Postulate 2 defines a rule for the conditional probability that connects two subsequent events (Born rule). The mean value of the physical quantity (1) manifested in the event $|\psi_{t_k}\rangle\langle\psi_{t_k}|$ is given, as it is easy to verify, by:

$$\langle\hat{o}\rangle = Tr[|\psi_{t_k}\rangle\langle\psi_{t_k}|\hat{o}] \quad (4)$$

149 The postulate 2 does not privilege either of the two directions of time. However, it is also possible
150 to introduce a time-oriented dynamics by defining the pair of amplitudes:

$$\begin{aligned} |\psi_t'\rangle &= \hat{S}|\psi_{t_k}\rangle; \text{ quantum 'forward' amplitude} \\ \langle\psi_t''| &= \langle\psi_{t_{k+1}}|\hat{S}^+; \text{ quantum 'backward' amplitude} \end{aligned} \quad (5)$$

to which the two time evolution equations, equivalent to Equation (2):

$$i\hbar\partial_t|\psi_t'\rangle = \widehat{H}|\psi_t'\rangle \text{ for } t \in [t_k, t_{k+1}] \text{ 'forward' evolution} \quad (6)$$

$$-i\hbar\partial_t\langle\psi_t''| = \widehat{H}\langle\psi_t''| \text{ for } t \in (t_k, t_{k+1}] \text{ 'backward' evolution} \quad (7)$$

151 are respectively associated. In general, however, it is $|\psi_t'\rangle_{t=t_{k+1}} \neq |\psi_{t_{k+1}}\rangle$ and $\langle\psi_t''|_{t=t_k} \neq \langle\psi_{t_k}|$.
 152 This circumstance is named 'quantum jump' or 'quantum discontinuity'. For $t \in (t_k, t_{k+1})$ it is formally
 153 possible to define the mean values $\langle\psi_t'|\widehat{O}|\psi_t'\rangle, \langle\psi_t''|\widehat{O}|\psi_t''\rangle$, but they have not a direct physical meaning as
 154 they are not manifested in an event.

Along this alternative route, the Born rule can be introduced as follows. Let $\widehat{A} = \sum_i a_i |a_i\rangle\langle a_i|$ be a physical quantity. Let us imagine $n \rightarrow \infty$ mental copies of the causal connection between two subsequent events (without intermediate events), and impose that these copies differ only for the final event. The final events will all be, by hypothesis, of the kind $|a_i\rangle\langle a_i|$; this is possible in virtue of the definition of \widehat{A} as a physical quantity, which assures the existence of a manifestation f with these images. The final 'average' event will then be:

$$\frac{\sum_{n \text{ mental copies}} |a_i\rangle\langle a_i|}{n} \rightarrow \sum_i P_i |a_i\rangle\langle a_i| = \Lambda \quad (8)$$

From (8) we have $\sum_i P_i = 1$, so that P_i is the probability of the manifestation of the $|a_i\rangle\langle a_i|$ event whose existence is guaranteed by the postulate 1. Since the initial event is fixed, the quantum forward amplitude at the instant immediately preceding the manifestation of the final event is also fixed and we denote it as:

$$|\psi\rangle = \sum_i c_i |a_i\rangle \quad (9)$$

155 Thus, the density operator $\rho = |\psi\rangle\langle\psi|$ associated with this amplitude is also fixed. The operator
 156 $|a_k\rangle\langle a_k|$ associated with the final event transforms $|\psi\rangle$ in $c_k |a_k\rangle$, and then ρ in $c_k^* c_k |a_k\rangle\langle a_k|$. The same
 157 operator transforms Λ in $P_k |a_k\rangle\langle a_k|$.

158 The coefficients c_i in Equation (9) evolve in time according to Equation (6) but their physical
 159 meaning remains undefined. We define it by imposing that the effects of the two transformations (of ρ
 160 and Λ) induced by the final event are equal, so that this event induces the transition $\rho \rightarrow \Lambda$. As a result
 161 of this definition we obtain $P_k = c_k^* c_k$ that is the Born rule.

The postulate 2 can therefore be replaced by the evolution Equation (6) for the forward amplitude, adding as a new postulate the transition $\rho \rightarrow \Lambda$ induced by the final event (projection postulate). It is important to note that, despite the apparent irreversibility implied by both the choice of a determined temporal direction and the decoherence implicit in the projection postulate, such construction is completely time-symmetrical. One could start from the evolution Equation (7) for the backward amplitude, keep the final event fixed and assume the initial event as a variable. In this case the density operator ρ will be the one associated with the backward amplitude at the moment of the initial event, while Λ will be the 'initial average event'. One will then have to impose that, as a result of the initial event, $\rho \rightarrow \Lambda$. Postulate 2 seems preferable because it avoids a separate postulate of projection. Before closing this section we would like to discuss briefly two valid concepts both for a manifestly time-symmetrical description and an apparently time-oriented formulation. Let us consider the event $|\psi_{t_k}\rangle\langle\psi_{t_k}|$. If

$$|\psi_{t_k}\rangle = \sum_{i=1}^n \lambda_i |\phi_i\rangle, \quad \lambda_i \in \mathbb{C} \quad (10)$$

162 then the diagonal elements $|\phi_i\rangle\langle\phi_i|$ in the expansion of $|\psi_{t_k}\rangle\langle\psi_{t_k}|$ are named 'virtual sub-events' of
 163 the event $|\psi_{t_k}\rangle\langle\psi_{t_k}|$. Crossing one of the two slits in the double slit experiment is a typical example of

164 virtual sub-event. The virtual sub-events are not manifested, that is no application $f' : t_k \rightarrow |\phi_i\rangle\langle\phi_i|$
 165 exists, as the application $f : t_k \rightarrow |\psi_{t_k}\rangle\langle\psi_{t_k}|$ is unique.

The second relevant point is that while the event $|\psi_t\rangle\langle\psi_t|$ represents the localization of the ‘quality’ ψ_t (and the physical quantities associated with it) in the time domain, as for the spatial localization some additional remarks are necessary. The three-dimensional space enters our scheme only through the form of the Hamiltonian \hat{H} . For example, posing:

$$\hat{H} = -\frac{\hbar^2}{2m}\Delta \quad (11)$$

where Δ is the Laplacian operator on the Euclidean three-dimensional space E^3 , the equation $i\hbar\partial_t|\psi_t\rangle = \hat{H}|\psi_t\rangle$ admits solutions dependent on $x \in E^3$:

$$|\psi_t\rangle = \sum_{x \in E^3} |x\rangle\langle x|\psi_t\rangle = \sum_{x \in E^3} |x\rangle\psi(x, t) \quad (12)$$

166 The operator impulse is then defined as $\hat{p} = -i\hbar\hat{\nabla}$, and it acts on the space of the solutions $\psi(x, t)$.

167 Equation (12) clearly shows that the operators $|x\rangle\langle x|$ are ‘virtual sub-events’ of the event $|\psi_t\rangle\langle\psi_t|$.
 168 This fact is generally denoted as ‘spatial delocalization’ of the wave-function $\psi(x, t)$, although an
 169 ‘a-spatiality’ is really involved here, in the sense that the ‘position’ is not actually manifested except in
 170 the particular case of a quality ψ_t coincident with a particular spatial position x .

171 It seems useful to point out here that the use of a Hamiltonian operator does not indicate the
 172 motion of anything, but rather it has to be seen as a ‘probability gradient’, a notion that unifies different
 173 formalisms such as Bohm potential and Feynman path integrals [22]. The fact that the application
 174 f introduced with the Postulate 1 is “sensitive” to time but not to space generates the well-known
 175 phenomenon of the non-separability of entangled amplitudes, well exemplified by the amplitudes of a
 176 pair of identical particles of spin 1/2 in a state of singlet. If one of the two particles is sent to a polarizer
 177 that separates the two beams with opposite spin values, each of which is subsequently directed to a
 178 detector, it is possible to have a “click” in one of the two detectors. This means that at that moment f
 179 localizes a precise spin value (better, a value of the spin component along the measurement axis) in a
 180 spatial region corresponding to the detector volume. With this, the virtual sub-event corresponding
 181 to the specific component of the singlet actually selected by the measurement becomes a real event.
 182 The spin of the other particle is therefore localized in time at the same instant. It remains not localized
 183 in space, but it can become so if the other particle is also subjected to a similar measurement.

184 3. General Remarks on Measurements

185 Temporal localization is associated with interaction micro-events (quantum jumps) and not with
 186 measurements performed by an experimenter. The measurement procedures were therefore absent
 187 in our previous discussion. It is only now that, having defined the context of a more fundamental
 188 quantum reality whose events are temporal localizations, we can move on to the description of
 189 measurement procedures as particular physical processes within that reality. These procedures involve
 190 particular macroscopic entities called “measurement apparatuses”; we must therefore define, in
 191 succession, classical macroscopic bodies and measurement apparatuses in the context of the quantum
 192 reality constituted by temporal localizations. We emphasize that this is a fundamental difference
 193 with respect to the conventional formulation, which is notoriously agnostic about the existence of a
 194 quantum reality. We call ‘classical macroscopic body’ a cluster of *events* whose averaged properties
 195 evolve deterministically over time, within the limits allowed by the finiteness of the quantum of
 196 action h .

Let us try to clarify formally the concept, at least sufficiently for the purposes of our argument. If the cluster were empty, that is, there were no events but only the possibility of their manifestation,

such possibility would be (we assume) expressed by quantum amplitude $|\psi\rangle$, to which the density operator $\rho' = |\psi\rangle\langle\psi|$ would correspond. We now postulate that $|\psi\rangle$ is decomposable in a basis of amplitudes $|\psi_k\rangle$, such that the actual manifestation of the events inside the cluster reduces ρ' to its diagonal component in this basis. In other terms, ρ' becomes a linear superposition ρ of density operators $\rho_k = |\psi_k\rangle\langle\psi_k|$:

$$\rho = \sum_k \lambda_k^* \lambda_k \rho_k; \quad \sum_k \lambda_k^* \lambda_k = 1; \quad \lambda_k = \langle\psi_k|\psi\rangle \quad (13)$$

197 When this happens we will say that the cluster is a classic macroscopic body. In practice,
198 (13) expresses the total decoherence of ρ in a basis selected by the dynamics of the events themselves.

199 Of course, the quantum equation of time evolution (whose validity is here assumed as universal)
200 applies to the operator ρ' , and it can be objected that in general this evolution does not lead to the
201 final 'state' (13). This objection, however, does not take into account that the quantum evolution of
202 the amplitudes (or more generally of the density operator), as it is usually defined, is relative to the
203 unperturbed situation between two successive events. It defines the probability of occurrence of the
204 next event, but the actual manifestation of this one modifies the initial condition of the next evolution
205 stage. Consequently, the quantum equation of time evolution must be applied starting from this new
206 condition and this happens many times in a single unit of time. The unitarity of the time evolution is
207 thus broken and the average result is decoherence. A classical macroscopic body is made decoherent
208 by the same discontinuities that constitute its essence, in a basis depending on its internal dynamics.

209 According to this view, a classical macroscopic body is an *object*, which is actualized in space and
210 time precisely because it is a complex of actualizations in the temporal domain (events). It is persistent
211 over time and endowed with a substance (its events) with attributes (the average properties of the
212 cluster). The evolution of these attributes can admit a classical (approximate) description. On the other
213 hand, the single event and the connection between two successive events represent phenomena that
214 cannot be classically described and therefore are, in this sense, 'entirely quantum'.

215 Let us consider now the elements $|\phi_k\rangle$ of a second Hilbert space \mathbf{H} (the "particle"); we assume
216 these elements are the eigenvectors of a physical quantity \hat{o} . If the manifestation of the event $|\phi_{k'}\rangle\langle\phi_{k'}|$
217 at the instant t_{ev} implies with certainty the transition $\lambda_k \rightarrow \delta_{kk'}$ for any value of k, k' and t_{ev} , this
218 transition is called a 'measurement' of \hat{o} , with 'result' $|\phi_{k'}\rangle\langle\phi_{k'}|$. The classical macroscopic body is then
219 called a 'measurement apparatus' of the physical quantity \hat{o} .

Denoting with $|\phi\rangle = \sum_k c_k |\phi_k\rangle$ the probability amplitude of the events $|\phi_k\rangle\langle\phi_k|$, evaluated at the
instant t , the density operator associated with the complex measurement apparatus plus particle is
then defined as $\rho|\phi\rangle\langle\phi|$ where ρ is defined by relation (13). Since the interaction between the particle
and the apparatus, mediated by the QJ, is diagonal on the basis $|\psi_k\rangle|\phi_k\rangle$, this operator evolves to:

$$\rho_c = \sum_k c_k^* c_k \lambda_k^* \lambda_k \rho_k |\phi_k\rangle\langle\phi_k| \quad (14)$$

220 This expression equates the diagonal component (on the basis $|\psi_k\rangle|\phi_k\rangle$) of the density operator
221 calculated in absence of quantum jumps, that is $\rho'|\phi\rangle\langle\phi|$, to which the same consideration previously
222 made for ρ' can be now applied. Measurements are made possible by selective coupling between the
223 'particle' operators $|\phi_k\rangle\langle\phi_k|$ and the (already) de-coherent ρ_k states of a classical macroscopic body.
224 Before the quantum jump, each ρ_k is coupled to any $|\phi_k\rangle\langle\phi_{k'}|$ and vice versa (without entanglement);
225 the quantum jump selects a specific coupling $\rho_k |\phi_k\rangle\langle\phi_k|$.

226 We deal with a two stage measurement process. The first stage involves only microscopic
227 components of the measurement apparatus and consists of the interaction that determines the
228 manifestation of the event $|\phi_{k'}\rangle\langle\phi_{k'}|$. The second stage consists of amplification/registration of
229 this event, which in turn determines the transition $\lambda_k \rightarrow \delta_{kk'}$. While the amplification/recording
230 phenomena can be described, with high precision, in classical language (which does not preclude their
231 exact description in quantum terms), the first stage is entirely quantum. The manifestation of $|\phi_{k'}\rangle\langle\phi_{k'}|$,
232 when considered in itself without regard of the following amplification/recording, rather represents

233 the localization of the value o_k of \hat{o} in the time domain. It is our opinion that these localizations
234 correspond to what other researchers have called 'hidden measurements' [23,24]. Several non-local or
235 contextual ' ε -machines' can be imagined. For example, in [25,26] the Born rule is exactly reproduced
236 by the selection of a specific 'loop' associated with a specific 'transaction'. However, these aspects are
237 beyond the scope of this paper and we leave them open. As it can be seen, with respect to standard
238 presentation the difference lies mainly in the differentiation that is made between events (quantum
239 jumps), which are localizations of packets of physical quantities in time domain, and measurement
240 procedures. To clarify further the concept, let us examine two concrete cases. Let us first imagine an
241 electron incident on a single slit screen. If the electron is absorbed by the screen, a quantum jump
242 occurs in the Hilbert space associated with the combination 'electron + atom of the screen absorbing
243 the electron'. In this jump, the quantum amplitudes that represented the electron in flight and the
244 atom in a stationary state are transformed into new amplitudes describing the electron bound to the
245 atom and this one (we say) in an excited orbital. This quantum jump takes place at a precise instant of
246 time, corresponding to the absorption of the electron; it localizes both the electron and the atom in time
247 domain. At the same time, the electron is localized in the three-dimensional space with an accuracy
248 defined by the volume occupied by the final atomic orbital. If the electron is not absorbed and passes
249 through the slit (negative interaction with the screen), it is only the quantum amplitude of the electron
250 to undergo a quantum jump at the time of passage. This jump converts the quantum amplitude of the
251 electron into a new amplitude that exhibits the phenomenon of diffraction. It localizes the electron in
252 time (moment of passage) and at the same time in three-dimensional space; the accuracy of spatial
253 localization is defined by the slit size. In these processes an interaction occurs (real in one case, negative
254 in the other) with temporal localization of a packet of physical quantities. Such localization is the
255 quantum jump. However, the localization event is not amplified (nor recorded) on a macroscopic
256 scale and there is therefore no measurement. The second case is that of an electron which impacts a
257 photographic plate and reduces a silver atom contained within a silver halide granule dispersed in the
258 plate emulsion. This case is quite similar to that of the real interaction with the screen atom, with the
259 difference, however, that the microscopic reduction event can be amplified macroscopically through
260 the photographic process (development, fixing, washing). During this process, the state of all the
261 atoms of the granule is at first changed (amplification); this change is successively made permanent
262 (recording) through the fixing process. The final result is a macroscopic modification: the appearance
263 of a darkened granule in the plate emulsion. The subsequent scanning of the plate can only detect an
264 already existing condition: the presence of a darkened grain.

265 The following inferences seem therefore clear: (1) the measurement process is a possible, but not
266 necessary, concomitance of the electron temporal localization event and these two things should not
267 be confused; (2) before the quantum jump, the electron is spatially delocalized in correspondence of
268 the positions of a multitude of silver atoms in different grains and each grain interacts with the *entire*
269 electron; (3) when the jump occurs, this delocalization is reduced and the electron is spatially localized
270 in correspondence of a specific silver atom within a single, specific grain; (4) before its interaction with
271 the electron, and regardless of it, each grain was actualized as a multitude of quantum jumps; the
272 interaction simply modifies the course of this actualization. Therefore, no Schrödinger cat situation
273 arises. This situation is modeled by Equation (14) as follows: $\lambda_k^* \lambda_k$ represents the fraction of silver
274 atoms in k -th grain; $c_k^* c_k$ is the probability of presence of the electron in correspondence of the k -th
275 grain. The quantum jump selects a specific state $\rho_k |\phi_k\rangle \langle \phi_k|$ with probability $\lambda_k^* \lambda_k c_k^* c_k$.

276 The main advantage of this proposal lies, in our view, in the most definite delimitation of the
277 role of measuring apparatus. To illustrate the concept, consider the distribution of molecular speeds
278 in a gas at a definite temperature. The properties of this distribution are determined by the impacts
279 between the gas molecules and between these and the molecules of the vessel walls. These impacts
280 are all QJs that localize molecules in space-time. However, none of these impacts, which contributes
281 to defining the classical system 'gas', is observed by the experimenter. In fact, the amplification and
282 recording of the single impact is lacking (the system is at the equilibrium and without memory) so

283 that we cannot speak of the energy and impulse exchanged in these impacts as ‘observables’. It is
 284 instead appropriate to talk about objective physical quantities associated with the single molecule or
 285 exchanged in the single impact.

286 Thus, it is justified the well-known fact that quantum mechanics can be successfully applied to
 287 phenomena that are not actually observed, such as the formation of a single chemical bond in a bulk
 288 of molecules or the impacts of gas molecules with the walls. Experimental apparatuses represent a
 289 condition in the definition of quantum amplitudes, but they are not their cause. Thus, even the known
 290 difficulties encountered in the application of the formalism to cosmology are removed, especially in
 291 the first moments after the initial singularity, when no observer and no setup could still exist.

292 4. Considerations about the “Cat Paradox”

In this section we apply the formalism defined in the previous sections to the concrete case of the pointer states of a measurement apparatus interacting with a micro-entity. In particular, we will consider the paradigmatic case of the “cat paradox” [27], trying to highlight how this paradox does not occur in the present formulation. In the conventional version of the QM the “cat paradox” is represented by the following situation:

$$A|G\rangle|D\rangle + B|E\rangle|L\rangle \quad (15)$$

where: G = nucleus in ground state, E = nucleus in excited state, L = live cat, D = dead cat. Let us see now how things are in the formulation we propose. First, the two states of the cat are decoherent because they are associated with distinct sets of actualizations (micro-events). Each of them is coupled with a distinct value of a dichotomous variable: “the QJ occurred” or “the QJ did not occur”. The QJ is here the nuclear decay. Consider the nuclear amplitude:

$$\psi_n = A|G\rangle + B|E\rangle \quad (16)$$

The occurrence of the QJ corresponds to the action of the projector $|G\rangle\langle G|$ on ψ_n ; the result of this action is $A|G\rangle$. The non-occurrence of the QJ corresponds to the action of the operator $1 - |G\rangle\langle G|$ on ψ_n ; the result of this action is $B|E\rangle$. We have therefore the two decoherent couplings $A|G\rangle|D\rangle$ and $B|E\rangle|L\rangle$ that originate the total density matrix:

$$\Omega = AA^*(|G\rangle\langle G|)(|D\rangle\langle D|) + BB^*(|E\rangle\langle E|)(|L\rangle\langle L|) \quad (17)$$

293 which is the particular form assumed by Equation (14) for the specific problem. The single experimental
 294 run begins with the preparation $(|E\rangle\langle E|)(|L\rangle\langle L|)$, corresponding to the fact that a QJ has not yet
 295 occurred. The nuclear amplitude evolves as a superposition of G and E until the decay occurs.
 296 When the decay occurs, the density matrix relative to the single run becomes $(|G\rangle\langle G|)(|D\rangle\langle D|)$.
 297 This sudden transition is the killing of the cat. The unitary time evolution of the superposition
 298 of G and E has no reflection on the status of the cat in the single run, except when the QJ occurs.
 299 What happens is that the QJ converts the qubit ψ_n to the corresponding bit “ E or G ”. After that
 300 the macroscopic measurement apparatus couples with this bit. Thus the QJ transforms quantum
 301 information in classical information.

302 The decoherence of the L , D states of the cat makes them refractory to the superposition, and
 303 therefore unsuitable to act as the basis states of a qubit that can be the input of a QJ. They can only
 304 read the occurrence (or non-occurrence) of the QJ. Instead, the states of the particles that contribute
 305 in a vertex of interaction to produce a QJ can undergo to a superposition and are in fact, generally,
 306 entangled. The unitary time evolution concerns the qubit before the QJ; it affects the apparatus only
 307 through the conversion of the qubit by the QJ. The time evolution of Ω is then non unitary.

308 In the conventional version, quantum amplitudes (bra or ket) are associated with the states of a
 309 system. It turns out therefore incomprehensible that the same physical situation (the cat + nucleus

310 complex) is simultaneously represented by a superposition and a mixture. Two “states” cannot in fact
 311 be superposed and incoherent at the same time. In this version, however, the amplitudes are associated
 312 with events and not with states of any system; moreover, the nature of this association is different for
 313 the superposition and for the mixture.

314 In the conceptual experiment of the cat, the superposition of amplitudes associated with the
 315 nucleus (the “qubit”) is relative to the two outcomes G and E , conditioned by past events (the
 316 “preparation”), of an event that has not yet occurred. The conjugated superposition is relative to the
 317 results, conditioned by future events (the “detection”), of a past event already happened. The elements
 318 of the density matrix of the cat + nucleus complex (the “bit”) are instead related to events actualized
 319 in the present moment and to their logical negatives: the single nucleus is “already decayed” (G) or
 320 “not-yet-decayed” (E).

As can be seen, the essential point is that the cat is a set of actualizations and its qualifications L and D represent two distinct complexes of classical properties a, b, \dots, z defined on this set, in a way such that:

$$L = a \wedge b \wedge c \dots \wedge z; \quad D = (\neg a) \vee (\neg b) \vee (\neg c) \dots \vee (\neg z) \implies L = \neg D \quad (18)$$

Moreover:

$$x \wedge (y \vee z) = (x \wedge y) \vee (x \wedge z); \quad x, y, z = a, b, \dots, z. \quad (19)$$

In this expressions the symbols \neg, \vee, \wedge represent respectively the negation, the inclusive disjunction (the Latin *vel*) and the conjunction of classical logic. We immediately see that the properties attributed to the cat do not respect the relations of quantum logic. The distributivity of \wedge with respect to \vee means that properties a, \dots, z are relative to a level of description that is enormously coarse if compared to the fineness of the quantum of action; on this level the possible non-commutativity of physical quantities does not play any role. A property of this type could be, for example, “inside the cat the blood circulation is active” or the opposite. It is evident that, with respect to the truth of statements of this kind, the quantum delocalization is irrelevant and we are therefore in the full domain of application of classical physics. Let us thus consider the quantum amplitude:

$$\psi = \alpha|D\rangle + \beta|L\rangle; \quad \alpha, \beta \in \mathbb{C}; \quad |\alpha|^2 + |\beta|^2 = 1. \quad (20)$$

The projector $|\psi\rangle\langle\psi|$ describes a set of classical properties, as requested, if and only if $|\alpha|^2 = 1$ or $|\beta|^2 = 1$. Otherwise, although it is a well-formed expression of quantum formalism, it will have an empty semantic set. It is the same situation that occurs in the grammar of the ordinary language with expressions like “the liquid pencil” or “the children of a sterile woman”. In terms of the axiomatic discussed in this paper, $|\psi\rangle\langle\psi|$ can be manifested as an event if and only if $|\alpha|^2 = 1$ or $|\beta|^2 = 1$:

$$(\exists t \in T, f: t \rightarrow |\psi\rangle\langle\psi|) \implies (|\alpha|^2 = 1) \vee (|\beta|^2 = 1) \quad (21)$$

321 Accordingly, in our re-formulation of quantum mechanics, the measurement apparatus is not
 322 in a superposition of pointer states. Therefore, if the measurement apparatus and the micro-entity
 323 undergoing the measurement are closed inside a box inaccessible to an external observer, who however
 324 knows the initial state of the complex apparatus + micro-entity, this observer cannot legitimately
 325 deduce that such complex is in a superposition state. In fact, this is not the law of evolution of this
 326 complex in our version of quantum mechanics. Therefore, paradoxes such as that of “Wigner’s friend”
 327 cannot arise, nor more elaborate paradoxes such as the one recently discussed by Frauchiger and
 328 Renner [28,29].

329 5. Quantum Jumps and Bits: Localization in Time as Information

In this section, in which we will take the liberty to be a little more speculative, we would like to reconsider the idea of ‘event’, understood as ‘localization in time’, from an informational perspective. It seems to us that a possible starting point in this direction is represented by the uncertainty principle.

In our proposal, this fundamental principle of QM describes the intrinsic limitation of the manifestation of physical quantities on a quantum scale (let us consider, for example, the a-spatiality already mentioned in the case of the position). An expression of type $\sigma(q)\sigma(p) \geq h/4\pi$ indicates that it is not possible to reduce the product of the amounts of delocalization $\sigma(q)$ of the position q and $\sigma(p)$ of the momentum p below the limit value h ; this value then sizes the volume of an elementary cell in the phase space. The volume occupied by a physical system in its phase space therefore contains a finite number of distinguishable states. The information associated with the manifestation of one of these states is therefore finite, though it may be enormous. Bekenstein estimated an upper bound for information I associated with a system with total energy E enclosed in a sphere of radius R in ordinary three-dimensional space [30]:

$$I = \log_2 n \leq \frac{2\pi ER}{\hbar c \ln 2} \quad (22)$$

330 The finiteness of I defines a range of *classical* values attributable to two non-commuting variables
 331 such as position and momentum. An examination of the system on a finer scale leads us into realms
 332 dominated by delocalization and entanglement, such as that of atomic orbitals and their transitions [31].
 333 On the other hand, a compromise between classical properties and quantum uncertainty can arise
 334 when weak measurements are performed [32].

A particular form of the Bekenstein constraint valid for confined systems within a horizon of events (it was originally deduced for black holes in [33]) is the following:

$$I = \frac{A}{4l^2} \quad (23)$$

335 where A is the horizon area and $l \approx 10^{-33}$ cm is the Planck length. I represents the information
 336 enclosed within the horizon and therefore 'lost' from the point of view of the world outside the
 337 horizon, for which it represents the entropy associated with the horizon.

338 Let us consider now the transition of a physical quantity, delocalized in time, to its condition
 339 completely localized in time, the passage we identified with the notion of 'event' or QJ. Such a passage
 340 corresponds to the acquisition of information on the temporal localization of the physical quantity (or
 341 the packet of physical quantities). If we compare with a metaphor inspired by information technology,
 342 the time domain to a memory storage device (we say a hard disk), then the 'event' is the *irreversible* act
 343 of writing a data packet on the disk. In systemic terms, we can talk about the informational openness
 344 of QM, correlated with the conversion of primordial non-local information into a measurable form
 345 according to Shannon and Turing. Primordial information is clearly a formal cause in the Aristotelian
 346 sense, with the additional characteristic of being synchronic and therefore very different from the
 347 diachronic efficient cause which is usual in physics (*dynamical* causality expressed by the unitary
 348 evolution of amplitudes). This one is probably only an appearance of this deeper formal causation,
 349 as perceived from the time domain. Bohm proposed the term 'active information' [34]. There are
 350 very interesting models on these aspects, such as the *implicate order* explored with non-commutative
 351 geometry by Basil Hiley, but here we will not go into details on this [35,36]. All this suggests that the
 352 natural habitat of QM is pre-temporal [37,38].

353 One can ask if there is no minimum proper time interval θ_0 between two successive temporal
 354 localizations of the same particle. One can also wonder whether the coordination of events by an
 355 observer is not limited within a horizon of radius ct_0 centered on the observer itself (c is the limit
 356 speed). We can attempt to estimate t_0 from the experimental value of the cosmological constant λ ,
 357 which is in the order of 10^{-56} cm⁻². Assuming that the origin of such a constant is the presence of a de
 358 Sitter horizon, the relation $\lambda = \frac{4}{3c^2 t_0^2}$ must hold, which provides $ct_0 \approx 10^{28}$ cm. The de Sitter horizon
 359 area is then $A \approx (10^{28} \text{ cm})^2$ and inserting this value into (23) we obtain $I \approx 10^{123}$.

360 We can divide the portion of the contemporaneousness space of the observer, internal to the
 361 observer de Sitter horizon, in 'cells' of volume $(c\theta_0)^3$, each corresponding to a distinguishable spatial
 362 localization. Since the radius of the horizon is ct_0 , the number of such cells is $N \approx [(ct_0)^3 / (c\theta_0)^3]$.

Each cell can be in one of two states: ‘on’ if a localization occurs in it, ‘off’ otherwise. The number of possible states is clearly 2^N and the information associated with these states is $\log_2(2^N) = N$. We assume that quantum jumps manifest the elementary components of the physical system within an elemental cell of volume h^3 in their phase space, so that each state will correspond to a cell of volume h^{3N} in the phase space of the total system. The logarithm of the number of states is therefore the same information I of (23) and we have $I \approx [(ct_0)^3 / (c\theta_0)^3]$. From this relation we obtain $c\theta_0 \approx 10^{-13}$ cm, a result that is of the same order of both the classical radius of the electron and the range of strong interactions (color confinement). The time interval $\theta_0 \approx 10^{-23}$ s is of the same order of the ‘chronon’ introduced by Caldirola in his classical theory of the electron, just as the time interval between two successive localizations of the electron in space-time [39,40].

If this reasoning is correct, the impact of the finiteness of I on the temporal localization process would consist in simultaneous appearance of two scales, both independent on cosmic time: one cosmological (de Sitter radius), the other at the particle level (chronon). This suggestion could open new perspectives of unification between elementary particle physics and cosmology.

We also observe that, starting from the two fundamental constants of the localization process, i.e., the intervals t_0 and θ_0 , it is possible to define a maximum acceleration $ct_0 / (\theta_0)^2$. On a spatial interval $c\theta_0$, corresponding to the typical scale of the elementary particles, this acceleration is reached if a speed variation $c\theta_0 / (d_P/c)$ is implemented in a temporal interval d_P/c , where $ct_0 / (\theta_0)^2 = c\theta_0 / (d_P/c)^2$. Substituting $I = [(ct_0) / (c\theta_0)]^3$ and $A = 4\pi(ct_0)^2$ in Equation (23), we can see that $d_P \approx l$. It is of course possible to proceed in reverse order, defining the Planck scale through the maximum acceleration, and thus obtain the (23). The foundation of (23) therefore appears to be the global-local connection manifested in the process of localization, rather than some form of “holographic principle”. This suggests a purely informational interpretation of the Planck scale. The connection of this scale with the universal gravitational constant could be accidental and perhaps due to the limitations imposed on the principle of local equivalence between gravity and inertia by the existence of a maximal acceleration. We leave this topic open for subsequent research work.

6. Quantum Computing in and Beyond Spacetime

In this section we will discuss the problem of the possible existence of spatiotemporal constraints on the quantum computing, raised by some authors [20,21]; our reference context will be the one described in the previous section. We will argue that such a constraint exists on the cosmological scale, but that it is in practice unattainable and, in any case, devoid of effects on the actually implementable quantum computing schemes. Our reasoning can be considered an answer to Davies [20]. We will start by considering the case of a single qubit:

$$\psi = \alpha|+\rangle + \beta|-\rangle \quad (24)$$

This qubit will be by hypothesis associated with a particle. We also assume that the basic amplitudes $|+\rangle$, $|-\rangle$ are spatially encoded, in the sense that the attribution of one of these two amplitudes to the particle corresponds to its localization in one of two distinct spatial regions. We can consider the actual case of a particle of spin 1/2 sent to a Stern-Gerlach analyzer which separates the two components of spin along the direction of the applied magnetic field. The click of the counter “+” downstream of the analyzer will be at the same time the measurement of the spin with result +1/2 and the spatial localization of the particle within the volume of the counter. A similar consideration will apply to the click of the “-” counter. Consider then a system of n particles, each associated with a qubit with basis amplitudes distinct from those of all the others. By encoding each of these amplitudes with a distinct spatial region, the total amplitude of the n particles will be a superposition of 2^n n -ples of distinct spatial regions. While the quantum computing occurs at the level of the phase relations between these n -ples, which are a-spatial and therefore not subject to any constraint of spatial nature, the situation is a little different for the single n -ple. It is indeed evident that every n -ple of space

403 regions must belong to space, and therefore be contained in it as a subset. Now, the maximum number
404 n of qubits with spatially codable basis amplitudes will be given by the maximum number of possible
405 spatial positions for a particle at a given moment, within the cosmological horizon. As we have argued
406 in the previous section, this number is $I \approx 10^{123}$. In other words, the number of qubits will be subject
407 to the Bekenstein limit $n \leq 10^{123}$. Naturally this limit is satisfied by all current and future quantum
408 computer projects. However, it is also possible to show that it is unreachable by computers made up
409 of ordinary matter with stable nuclei and electrons. The average density of ordinary matter in the
410 Universe (with the exclusion of dark matter and dark energy) is $\approx 5 \times 10^{-31}$ g/cm³. Almost all of the
411 mass is represented by nucleons, with an individual mass of 1.67×10^{-24} g. It is obtained hence a
412 nucleonic density of 3×10^{-7} /cm³. About half of the nucleons consists of protons and assuming that
413 their charge is neutralized by as many electrons, an electronic density of 1.5×10^{-7} /cm³ is obtained.
414 We have therefore a particle density of 4.5×10^{-7} /cm³. Assuming a de Sitter radius of 1.4×10^{28} cm,
415 there are therefore in total 0.5×10^{79} particles (nucleons and electrons). A lot less than 10^{123} .

416 7. Comparisons with Other Approaches

417 No theory is born of nothingness, and every scholar is well aware of walking with others.
418 In this section we aim to take stock of the kinships that have been a source of inspiration for us.
419 Although the formal tools introduced in this work are the same as the current formulation of the
420 QM, the prescriptions on their use are different, and this leads to a difference in the predictions
421 obtainable with the two versions of the theory. Naturally, nothing new can be expected regarding
422 the description of what in the usual jargon can be defined as “micro-systems” represented by “pure
423 states”; therefore, the representation of the configuration in isolation of atoms, atomic nuclei and
424 molecules—for example—will be the same. However, there will be significant differences in the
425 treatment of interacting systems, in particular those with many particles, since they will present, in
426 appropriate limit conditions, transition phenomena to the status of classical objects not described
427 in the usual version. In our proposal, therefore, the inclusion of a specific ontological element (the
428 identification of the reduction of the amplitude with the physical phenomenon of the “jump”) leads
429 to predictive differences not obtainable in the context of a simple interpretation of the theory in its
430 current formulation.

431 Other approaches try to obtain similar results by modifying the dynamics of the theory, a
432 stratagem that is not used in the context of our proposal. This is the case of spontaneous localizations
433 contemplated by the Ghirardi-Rimini-Weber (GRW) approach, both in the form of “hits” and as
434 continuous processes obtained by adding appropriate stochastic terms to the quantum motion
435 equation [41–44]. In particular, the version known as GRW-flash [45–47] may have some similarities
436 with our proposal, so it is important to summarize also the differences. First of all, we do not
437 hypothesize spontaneous localizations (that is, independent from ordinary interactions) that happen
438 randomly and that remain elusive on the experimental plan. Instead, we identify the processes of
439 reduction of the wave function with specific objective physical phenomena whose existence is today
440 experimentally well demonstrated: the quantum jumps. These jumps are induced by the usual physical
441 interactions (electromagnetic, weak, nuclear etc.).

442 Our description, therefore, does not contemplate the possibility of spontaneous flashes
443 distinguished from ordinary interactions, but has instead to do with a quantum discontinuity connected
444 with such interactions [31]. This point is relevant with reference to the measurement theory (see the
445 conclusion of [47]). Moreover, we see no reason to favor the positional basis and we mean the
446 localization in a temporal, not a spatial sense. What is instantiated is the projector on the quantum
447 amplitude and not the spatial position. We see the peculiarity of the quantum description in the fact
448 that, according to it, the ordinary interactions modify the amplitudes according to one or the other of
449 two causal schemes that are mutually irreducible and, at the same instant of time, mutually exclusive:
450 the unitary evolution and the QJ. To the dynamical causation (which involves the transfer of energy

451 between spatio-temporal regions) a formal causation is added (which involves a certain localization
452 information entering the spatio-temporal domain).

453 The appearance of a particle scale in the context of the basic formalism recalls the representation
454 of “corpuscles” as localized concentrations of field energy, guided by a pilot wave; a representation
455 typical of non-linear theories such as those proposed by the de Broglie school (see e.g., [48,49]).
456 The difference, however, is that in the context of the present approach (which preserves the linearity of
457 conventional formalism) we describe the temporal localization of physical quantities, rather than the
458 spatial localization of a pre-existent globule. In other words, our idea of objectivity of the physical
459 world mirrors an ontology of events rather than substances, according to Russell and Whitehead’s
460 classic ideas.

461 In describing both the relata and the relations, i.e., quantum jumps and transition amplitudes
462 respectively, we have used their full temporal symmetry offered by the QM in its usual version.
463 We have therefore considered both the transition amplitude and its conjugate and, for the QJ, both
464 the ket and its conjugated bra. Both these choices recall the Transactional Interpretation of the QM
465 (TIQM) introduced by Cramer in the 1980s [50–52] and advocated in particular by Kastner (see eg [53]
466 for a general presentation of her views). As far as we are concerned, we have carefully considered
467 the TIQM since its appearance, letting us be inspired by its principles. However, we have developed
468 these principles in a different form from the one originally proposed by Cramer [26,54]. Our personal
469 elaboration naturally connects to the postulates presented in this article and clarifies them. However,
470 it has led us on a path that differs from the TIQM for some significant differences, which we will now
471 try to summarize.

472 The basis of transactional narrative is the simultaneous emission of the “offer” and its conjugated
473 (the “confirmation”), respectively in the future and past light cone of the emission point. The same
474 status of reality is attributed to the offer and the confirmation and the superposition of offers and
475 confirmations induces the exchange of quanta. The emitter is therefore also an absorber, and the whole
476 description is traced back to specific properties of the absorbers [55]. It seems to us that this description
477 concerns the propagation of specific fields on the temporal (or spatio-temporal) domain and is therefore
478 internal to this domain. It involves, even in the process of double emission or absorption-emission, the
479 only efficient diachronic causality; that is, it has to do with a dynamical causality in space-time. In fact
480 the reference model assumed by TIQM is the Wheeler-Feynman electrodynamics [50].

481 The basis of our reformulation is instead the localization of physical quantities in the temporal
482 domain. The causality involved in the localization process is formal, not efficient; it is synchronic
483 (in that it connects the atemporal realm of quantities, that is, Hilbert space, to temporal domain),
484 rather than diachronic (connection between instants). There is no process of emission or absorption
485 of quantum fields in the classical sense of the term. There is no object, field or particle, which acts
486 as emitter-absorber. The connection between events is timeless (the time labels the different *actual*
487 localizations) and the transition amplitudes are a time-symmetrical aspect of this connection: there is
488 no propagation of fields in time or space-time. The role of the offer-confirmation pair is assumed here
489 by a projector, that is, an algebraic entity that represents a *transformation*, and which can be matched
490 with the elements of a classical propositional calculus. To be more exact, we consider a cosmic process
491 of *manifestation* that associates a temporal label to the projectors, thus carrying out a localization action
492 to which information is associated, which is thus “entered” in the temporal domain; and in this sense
493 we speak of a formal cause. The process we are trying to describe seems to be more fundamental than
494 what can be captured with the ontological categories of a classical field theory, even if extended in a
495 time-symmetric and non-local sense and applied to quantum fields. It is sufficient to consider that the
496 potential non-separability of amplitudes appears here on a native level.

497 In this sense, perhaps the closest suggestion is the implicate order of Bohm-Hiley [56], however,
498 with the important clarification that its explication occurs at the level of quantum discontinuity. As we
499 have seen, informational considerations on discontinuity seem to connect in a natural way to two

500 important scales: that of elementary particles and that of Planck, perhaps opening up new perspectives
501 of foundational research on a theory of inestimable success like the QM.

Another research program with which our approach has clear convergences is that of decoherence [57–62]. Therefore, it seems opportune to emphasize here the similarities and differences, and we think that the best way to do this is to discuss briefly an elementary ideal case. Consider a classical macroscopic system; as we have seen, it consists of a normally very large number of elementary quantum components (for example, molecules). Let S be one of these components and E the complex consisting of the remaining components. Let us consider a specific interaction between S and the individual elements of E such that the total amplitude of $S + E$ at time t is:

$$|\psi\rangle = \alpha|s_1\rangle|e_1\rangle + \beta|s_2\rangle|e_2\rangle \quad (25)$$

502 For simplicity, we have considered only two (orthogonal) basis amplitudes s_1 and s_2 of S and
503 two (not necessarily orthogonal) amplitudes e_1 and e_2 of E . Now consider the trace of $|\psi\rangle\langle\psi|$ on the
504 states of E ; it will contain terms of interference proportional to the real part of the scalar product of
505 the two states of E . If these ones are orthogonal, the interference disappears, whereas in the general
506 case it will be attenuated. Because S is randomly chosen among the elementary components of the
507 macroscopic system, and this random choice determines the components of E , we have that the
508 possible existence of an interaction of this type between S and E , independent on this choice, leads
509 to a quantum decoherence between the elementary components of the system. This decoherence
510 makes the system, in a certain sense, “more classical” because it diagonalizes the density matrix of
511 each of its components, averaged on the degrees of freedom of the others, on a basis selected by the
512 interaction itself. Of course, coherence does not disappear, it is simply transferred from the basis
513 elements of S to the amplitudes of $S + E$. This is the mechanism underlying the theory of decoherence.
514 In our approach all this remains true. Now, however, at a given instant of time the total amplitude
515 expressed by the preceding equation “collapses” into one of the basis amplitudes of S (s_1 or s_2) due to a
516 quantum jump. The probability of the two results is defined by the diagonal components of the density
517 matrix in the basis s_1, s_2 . After the collapse, the off-diagonal coefficients reappear as a result of unitary
518 evolution, until a subsequent quantum jump. Thus the *mean* density matrix will have both diagonal
519 and off-diagonal terms. The decay of the off-diagonal terms in a “multi-hit” process (where each “hit”
520 is a QJ) was analyzed by Simonius in a pioneering work [63]. The decoherence time is a function of
521 the frequency of the Rabi oscillations of the free S system, of the degree of orthogonality between the
522 amplitudes of E and of the (normally Poissonian) temporal distribution of “hits”, in turn dependent on
523 state variables such as temperature and pressure. The mean effect of a succession of quantum jumps
524 on the evolution of the density matrix therefore seems to be what the theory of decoherence describes.
525 From our point of view, however, the fundamental process is a piecewise unitary evolution, whose
526 intervals are joined by genuinely non-unitary discontinuities.

527 8. Conclusions

528 As is well known, the absence of trajectories in quantum formalism and the instantaneous
529 cancellation of the wave-function when the particle impacts on an absorber make any interpretation of
530 Quantum Mechanics (QM), based on a realistic classical approach, extremely difficult. This difficulty
531 has generated the two still dominant trends in the debate about the nature of QM. On the one hand,
532 the idea of the incompleteness of the theory goes back to Einstein and arrives to current proposals like
533 that of 't Hooft. On the other hand, the ‘pragmatic’ approach of Bohr is centered on what the observer
534 can say of the world through measurement procedures (for a good recent review, see [1]). It should be
535 said that none of the two trends provides universally shared answers for the weirdest aspects of QM.
536 We recall that the ‘realistic’ and ‘pragmatic’ trends have been established long before the experimental
537 confirmation of non-local aspects. If, for the Copenhagen view, non-locality is an ‘unexpected host’, for
538 realistic theories it is difficult to reconcile QM and relativity. Both of the interpretative lines have tried

539 to retain the image of persistent micro-physical object bearers of persistent properties. Realists used
540 'globules' driven by a medium, while pragmatists saw quantum amplitudes as descriptors of the 'state'
541 of a 'system'. Our re-reading of QM basic postulates identifies the 'quantum jump' with the notion of
542 'physical event', i.e., the temporal localization of a set of physical quantities, without any necessary
543 relation with the measurement processes and apparatus. The causal connections between events
544 is assured by the unitary time evolution of amplitudes, corresponding to a condition of temporal
545 de-localization of those same quantities. This connection (if any) is probabilistic, and is described
546 by the Born rule. No 'micro-object' is assumed in the time interval between two subsequent events.
547 The quantum amplitudes associated with the preparation or post-selection are therefore not 'states'
548 of any 'system'; in particular, a linear superposition of these amplitudes has not to be intended as a
549 superposition of 'states'. Temporal localizations of physical quantities thus assume the role of primary
550 elements of physical reality, with the result that this one is made up of events, and no longer objects.

551 The Hilbert space thus becomes the basic mathematical structure that allows the definition
552 of events as projection operators on the one hand, and the specification of the conditional
553 probability of causally related events on the other. This approach eliminates the fundamental role
554 of measurement-based notions (such as that of 'observable') while retaining the potentiality of the
555 conventional formalism. Detaching the meaning of quantum mechanical formalism from the narrow
556 situation represented by the usual experimental setup with the stages of preparation, propagation
557 and observation broadly extends the scope of application of formalism itself. The widespread use of
558 formalism that has been made over the decades to describe the structure of matter (particles, nuclei,
559 atoms, molecules, condensed states) is in this way justified.

560 The quantum jump is a non-unitary operation that converts quantum information (encoded
561 in forward or backward amplitude) into classical information; an operation which is represented
562 by an appropriate projector of a Hilbert space. The QJ consists in the temporal localization of the
563 physical quantities summarized in this projector. "Matter" is understood here as the complex of
564 these localizations and not as some kind of support for localized quantities. Each QJ is an elementary
565 interaction in the course of which a quantum of action is exchanged and therefore materializes a single
566 elementary cell (bit) in the phase space of a physical system. An analysis of the cosmological limits to
567 positional information associated with these localizations was carried out in Section 5. It is important
568 not to confuse this information with that processed by a quantum computer, as the Universe or a
569 computer that simulates it. The cosmological limits induced on this second information are analyzed
570 in Section 6 and the results are congruent with the well known calculation of Lloyd [64]. Differently
571 from Lloyd's assumptions, the concept of "event", which is here distinct from that of "observation",
572 does not imply in itself any irreversibility. As a result, most of the QJs are not registered.

573 Quantum information is processed between two successive QJs, causally connected through a
574 transition amplitude. This processing does not "take place" in the usual sense of the term because the
575 quantum superposition, considered in the time interval between the two QJs, is a pure mathematical
576 construct (Section 2) that evolves only in the sense of its parametric dependence on the instant of the
577 second QJ (forward amplitude) or first QJ (backward amplitude). Not surprisingly, the attempt to
578 analyze this evolution in spatio-temporal terms leads to virtual trajectories joining virtual sub-events,
579 for example the two paths in the double slit experience. These paths are naturally interfering and it has
580 been argued that this is the origin of the hyper-Turing nature of quantum computing [65]. Taking this
581 suggestion, an important field that opens to further investigations is that of the clarification of the
582 relationships between the hyper-computational aspects of quantum computing and the non-local
583 structure of elementary interactions modeled by quantum theories. The structure seems to indicate an
584 emergent aspect of the spatio-temporal ordering of events.

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