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# 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 to which 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 on the particle scale, of the atomic nuclei, of atoms, of molecules, of condensed matter. Those same 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's 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

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

35 It is noteworthy first of all that the QJ is an event in the history of the single nucleus; identical  
36 nuclei simultaneously prepared in the same way will decay at different times. Therefore the time  
37 evolution of the set of all these nuclei will lead to a mixture consisting of a decreasing fraction of  
38 non-decayed nuclei (whose amplitudes will be expressed by the same superposition of Radium 226  
39 and Radon 222) and a growing fraction of Radon 222. Second, the decay, that is the QJ, is an objective  
40 physical fact. Indeed a detector placed near the nucleus that undergoes the decay will detect an alpha  
41 particle, product of the decay (and possibly the gamma photon of rearrangement). By applying the  
42 principles of conservation of physical quantities such as charge, energy and impulse, we obtain that  
43 the quantities transported by the decay products are those related to the transformation of Radium  
44 226 in Radon 222. Since the emission of these products is instantaneous with respect to the unitary  
45 evolution of the nuclear amplitude, it follows that the QJ is instantaneous on the scale of this second  
46 process (and it can be assumed that it is instantaneous in the strict sense).

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

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

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

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

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

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

111 This formulation assigns the same theoretical and experimental significance to the two inseparable  
112 and complementary aspects, the 'time localized' (QJs) and the 'time de-localized' (amplitudes), of  
113 the quantum world. The relationship between these two aspects can be described in terms of the  
114 relationship between quantum information coded in the Hilbert space and classical information  
115 produced in the QJs. In particular, the Bekenstein limit becomes a limit on classical information which  
116 can be expressed in a finite volume of space by the QJs. If this limit has to be finite, the temporal  
117 de-localization must be limited both above, on the cosmological scale, and below. This last constraint  
118 determines the appearance of a scale of elementary particles, an element which is not explicit in the  
119 usual formulation of the QM. The evolution of the superposition of amplitudes in a quantum computer,  
120 however, does not happen in spacetime. Therefore this evolution does not seem to be limited by  
121 spatio-temporal constraints, which instead can afflict the input-output operations. It is in these terms  
122 that the recent debate on the possibilities of quantum computing raised by Davies and Aaronson  
123 [20,21] should be considered.

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

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

## 132 2. Rewriting quantum postulates

133 In this section we present a reformulation of the basic concepts of the QM according to the  
134 recognition of the fundamental nature of the QJs as events on the quantum scale.

135 We assume two primitive theoretical concepts:

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

138  
139 Postulate 1;  $\exists E \subset T$  such that:

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

144 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  
145 self-adjoint operator on  $\mathbf{H}$ ;  $t_k$  is the 'instant' when the event 'occurs'. The postulate 1 defines a causal  
146 structure of events based on a conditional probability. Let us consider now a linear operator  $\hat{o}$  on  $\mathbf{H}$ ,  
147 which is diagonal in the orthonormed and complete basis  $|\phi_i\rangle; i = 1, 2, 3, \dots$

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

148 If  $o_i \in \mathbb{R}$  and each  $|\phi_i\rangle\langle\phi_i|$  is a possible image of the application  $f$  then  $\hat{o}$  is called 'physical  
149 quantity' on the space  $\mathbf{H}$ .

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

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

152 with

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

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

154 Postulate 2 defines a rule for the conditional probability that connects two subsequent events  
155 (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  
156 it is easy to verify, by:

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

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

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

159 to which the two time evolution equations, equivalent to eq.(2):

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

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

160 are respectively associated. In general, however, is

161  $|\psi_t'\rangle_{t=t_{k+1}} \neq |\psi_{t_{k+1}}\rangle$  and  $\langle\psi_t''|_{t=t_k} \neq \langle\psi_{t_k}|$ . This circumstance is named 'quantum jump' or 'quantum  
162 discontinuity'. For  $t \in (t_k, t_{k+1})$  it is formally possible to define the mean values  $\langle\psi_t'|\hat{o}|\psi_t'\rangle, \langle\psi_t''|\hat{o}|\psi_t''\rangle$ ,  
163 but they have not a direct physical meaning as they are not manifested in an event.

164 Along this alternative route the Born rule can be introduced as follows. Let  $\hat{A} = \sum_i a_i |a_i\rangle\langle a_i|$   
165 be a physical quantity. Let us imagine  $n \rightarrow \infty$  mental copies of the causal connection between two  
166 subsequent events (without intermediate events), and impose that these copies differ only for the  
167 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  
168 the definition of  $\hat{A}$  as a physical quantity, which assures the existence of a manifestation  $f$  with these  
169 images. The final 'average' event will then be:

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

170 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  
171 whose existence is guaranteed by the postulate 1. Since the initial event is fixed, the quantum forward  
172 amplitude at the instant immediately preceding the manifestation of the final event is also fixed and  
173 we denote it as:

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

174 Thus, the density operator  $\rho = |\psi\rangle\langle\psi|$  associated with this amplitude is also fixed. The operator  
175  $|a_k\rangle\langle a_k|$  associated with the final event transforms  $|\psi\rangle$  in  $c_k |a_k\rangle$ , and then  $\rho$  in  $c_k^* c_k |a_k\rangle\langle a_k|$ . The same  
176 operator transforms  $\Lambda$  in  $P_k |a_k\rangle\langle a_k|$ .

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

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

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

193 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'  
194 of 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  
195 of virtual sub-event. The virtual sub-events are not manifested, that is no application  $f' : t_k \rightarrow |\phi_i\rangle\langle\phi_i|$   
196 exists, as the application  $f : t_k \rightarrow |\psi_{t_k}\rangle\langle\psi_{t_k}|$  is unique.

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

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

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

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

203 The operator impulse is then defined as  $\hat{p} = -i\hbar\hat{\nabla}$ , and it acts on the space of the solutions  
 204  $\psi(x, t)$ . The eq. (12) clearly shows that the operators  $|x\rangle\langle x|$  are 'virtual sub-events' of the event  $|\psi_t\rangle\langle\psi_t|$ .  
 205 This fact is generally denoted as 'spatial delocalization' of the wave-function  $\psi(x, t)$ , although an  
 206 'a-spatiality' is really involved here, in the sense that the 'position' is not actually manifested except in  
 207 the particular case of a quality  $\psi_t$  coincident with a particular spatial position  $x$ .

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

### 221 3. General remarks on measurements

222 Temporal localization is associated with interaction micro-events (quantum jumps) and not with  
 223 measurements performed by an experimenter. The measurement procedures were therefore absent  
 224 in our previous discussion. It is only now that, having defined the context of a more fundamental  
 225 quantum reality whose events are temporal localizations, we can move on to the description of  
 226 measurement procedures as particular physical processes within that reality. These procedures  
 227 involve particular macroscopic entities called "measurement apparatuses"; we must therefore define, in  
 228 succession, classical macroscopic bodies and measurement apparatuses in the context of the quantum  
 229 reality constituted by temporal localizations. We emphasize that this is a fundamental difference respect  
 230 to the conventional formulation, which is notoriously agnostic about the existence of a quantum  
 231 reality. We call 'classical macroscopic body' a cluster of *events* whose averaged properties evolve  
 232 deterministically over time, within the limits allowed by the finiteness of the quantum of action  $h$ .

233 Let us try to formally clarify the concept, at least sufficiently for the purposes of our argument.  
 234 If the cluster were empty, that is, there were no events but only the possibility of their manifestation,  
 235 the latter would be (we assume) expressed by quantum amplitude  $|\psi\rangle$ , to which the density operator  
 236  $\rho' = |\psi\rangle\langle\psi|$  would correspond. We now postulate that  $|\psi\rangle$  is decomposable in a basis of amplitudes  
 237  $|\psi_k\rangle$ , such that the actual manifestation of the events inside the cluster reduces  $\rho'$  to its diagonal  
 238 component in this basis. In other terms,  $\rho'$  becomes a linear superposition  $\rho$  of density operators  
 239  $\rho_k = |\psi_k\rangle\langle\psi_k|$ :

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

240 When this happens we will say that the cluster is a classic macroscopic body. In practice, (13)  
241 expresses the total de-coherence of  $\rho$  in a basis selected by the dynamics of the events themselves.

242 Of course, the quantum equation of time evolution (whose validity is here assumed as universal)  
243 applies to the operator  $\rho'$ , and it can be objected that in general this evolution does not lead to the final  
244 'state' (13). This objection, however, does not take into account the fact that the quantum evolution of  
245 the amplitudes (or more generally of the density operator), as it is usually defined, is relative to the  
246 unperturbed situation between two successive events. It defines the probability of occurrence of the  
247 next event, but the actual manifestation of the latter modifies the initial condition of the next evolution  
248 stage. Of consequence, the quantum equation of time evolution must be applied starting from this new  
249 condition and this happens many times in a single unit of time. The unitarity of the time evolution is  
250 thus broken and the average result is de-coherence. A classical macroscopic body is made de-coherent  
251 by the same discontinuities that constitute its essence, in a basis chosen by its internal dynamics.

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

258 Let us consider now the elements  $|\phi_k\rangle$  of a second Hilbert space  $\mathbf{H}$  (the "particle"); we assume  
259 these elements are the eigenvectors of a physical quantity  $\hat{o}$ . If the manifestation of the event  $|\phi_{k'}\rangle\langle\phi_{k'}|$   
260 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  
261 transition is called a 'measurement' of  $\hat{o}$ , with 'result'  $|\phi_{k'}\rangle\langle\phi_{k'}|$ . The classical macroscopic body is then  
262 called a 'measurement apparatus' of the physical quantity  $\hat{o}$ .

263 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  
264 instant  $t$ , the density operator associated to the complex measurement apparatus plus particle is then  
265 defined as  $\rho|\phi\rangle\langle\phi|$  where  $\rho$  is defined by relation (13). Since the interaction between the particle and  
266 the apparatus, mediated by the QJ, is diagonal on the basis  $|\psi_k\rangle|\phi_k\rangle$ , this operator evolves to:

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

267 This expression equates the diagonal component (on the basis  $|\psi_k\rangle|\phi_k\rangle$ ) of the density operator  
268 calculated in absence of quantum jumps, that is  $\rho'|\phi\rangle\langle\phi|$ . To the latter operator can be now applied  
269 the same considerations previously done for  $\rho'$ . Measurements are made possible by selective  
270 coupling between the 'particle' operators  $|\phi_k\rangle\langle\phi_k|$  and the (already) de-coherent  $\rho_k$  states of a classical  
271 macroscopic body. Before the quantum jump, each  $\rho_k$  is coupled to any  $|\phi_k\rangle\langle\phi_k|$  and vice versa  
272 (without entanglement); the quantum jump selects a specific coupling  $\rho_k|\phi_k\rangle\langle\phi_k|$ .

273 We have to do with a two stage measurement process. The first stage involves only microscopic  
274 components of the measurement apparatus and consists of the interaction that determines the  
275 manifestation of the event  $|\phi_{k'}\rangle\langle\phi_{k'}|$ . The second stage consists of amplification/registration of  
276 this event, which in turn determines the transition  $\lambda_k \rightarrow \delta_{kk'}$ . While the amplification/recording  
277 phenomena can be described, with high precision, in classical language (which does not preclude their  
278 exact description in quantum terms), the first stage is entirely quantum. The manifestation of  $|\phi_{k'}\rangle\langle\phi_{k'}|$ ,  
279 when considered in itself without regard of the following amplification/recording, rather represents  
280 the localization of the value  $o_{k'}$  of  $\hat{o}$  in the time domain. It is our opinion that these localizations  
281 correspond to what other researchers have called 'hidden measurements' [23,24]. Several non-local or  
282 contextual ' $\varepsilon$ -machines' can be imagined. For example, in [25,26] the Born rule is exactly reproduced  
283 by the selection of a specific 'loop' associated with a specific 'transaction'. However, these aspects  
284 are beyond the scope of this paper and we leave them open. As it can be seen, the difference with

285 standard presentation lies mainly in the differentiation that is made between events (quantum jumps),  
286 which are localizations of packets of physical quantities in time domain, and measurement procedures.  
287 To further clarify the concept, let's examine two concrete cases. Let's first imagine an electron incident  
288 on a single slit screen. If the electron is absorbed by the screen, a quantum jump occurs in the Hilbert  
289 space associated with the combination 'electron + atom of the screen absorbing the electron'. In this  
290 jump, the quantum amplitudes that represented the electron in flight and the atom in a stationary state  
291 are transformed into new amplitudes describing the electron bound to the atom and the latter (we  
292 say) in an excited orbital. This quantum jump takes place at a precise instant of time, corresponding  
293 to the absorption of the electron; it localizes both the electron and the atom in time domain. At the  
294 same time, the electron is localized in the three-dimensional space with an accuracy defined by the  
295 volume occupied by the final atomic orbital. If the electron is not absorbed and passes through the slit  
296 (negative interaction with the screen) it is only the quantum amplitude of the electron to undergo a  
297 quantum jump at the time of passage. This jump converts the quantum amplitude of the electron into  
298 a new amplitude that exhibits the phenomenon of diffraction. It localizes the electron in time (moment  
299 of passage) and at the same time in three-dimensional space; the accuracy of spatial localization is  
300 defined by the slit size. In these processes an interaction occurs (real in one case, negative in the other)  
301 with temporal localization of a packet of physical quantities. Such localization is the quantum jump.  
302 However, the localization event is not amplified (nor recorded) on a macroscopic scale and there is  
303 therefore no measurement. The second case is that of an electron which impacts a photographic plate  
304 and reduces a silver atom contained within a silver halide granule dispersed in the plate emulsion. This  
305 case is quite similar to that of the real interaction with the screen atom, with the difference, however,  
306 that the microscopic reduction event can be amplified macroscopically through the photographic  
307 process (development, fixing, washing). During this process, the state of all the atoms of the granule is  
308 at first changed (amplification); this change is successively made permanent (recording) through the  
309 fixing process. The final result is a macroscopic modification: the appearance of a darkened granule in  
310 the plate emulsion. The subsequent scanning of the plate can only detect an already existing condition:  
311 the presence of a darkened grain.

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

323 The main advantage of this proposal lies, in our view, in the most definite delimitation of the  
324 role of measuring apparatus. To illustrate the concept, consider the distribution of molecular speeds  
325 in a gas at a definite temperature. The properties of this distribution are determined by the impacts  
326 between the gas molecules and between these and the molecules of the vessel walls. These impacts  
327 are all QJs that localize molecules in space-time. However, none of these impacts, which contributes  
328 to defining the classical system 'gas', is observed by the experimenter. In fact, the amplification and  
329 recording of the single impact is lacking (the system is at the equilibrium and without memory) so  
330 that we cannot speak of the energy and impulse exchanged in these impacts as 'observables'. It is  
331 instead appropriate to talk about objective physical quantities associated with the single molecule or  
332 exchanged in the single impact.

333 Thus, it is justified the well-known fact that quantum mechanics can be successfully applied to  
334 phenomena that are not actually observed, such as the formation of a single chemical bond in a bulk

335 of molecules or the impacts of gas molecules with the walls. Experimental apparatuses represent a  
 336 condition in the definition of quantum amplitudes, but they are not their cause. Thus, even the known  
 337 difficulties encountered in the application of the formalism to cosmology are removed, especially in  
 338 the first moments after the initial singularity. When no observer and no setup could still exist.

#### 339 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 de-coherent 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 has 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  $\psi_n$ ; 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  $\psi_n$ ; 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:

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

340 which is the particular form assumed by Eq. (14) for the specific problem. The single experimental run  
 341 begins with the preparation  $(|E\rangle\langle E|)(|L\rangle\langle L|)$ , corresponding to the fact that a QJ has not yet occurred.  
 342 The nuclear amplitude evolves as a superposition of  $G$  and  $E$  up when the decay occurs. When the  
 343 decay occurs, the density matrix relative to the single run becomes  $(|G\rangle\langle G|)(|D\rangle\langle D|)$ . This sudden  
 344 transition is the killing of the cat. The unitary time evolution of the superposition of  $G$  and  $E$  has no  
 345 reflection on the status of the cat in the single run, except when the QJ occurs. What happens is that the  
 346 QJ converts the qubit  $\psi_n$  to the corresponding bit "E or G". After that the macroscopic measurement  
 347 apparatus couples with this bit. Thus the QJ transforms quantum information in classical information.

348 The decoherence of the  $L$ ,  $D$  states of the cat makes them refractory to the superposition, and  
 349 therefore unsuitable to act as the basis states of a qubit that can be the input of a QJ. They can only  
 350 read the occurrence (or non-occurrence) of the QJ. Instead the states of the particles that contribute  
 351 in a vertex of interaction to produce a QJ can undergo to a superposition and are in fact, generally,  
 352 entangled. The unitary time evolution concerns the qubit before the QJ; it affects the apparatus only  
 353 through the conversion of the qubit by the QJ. The time evolution of  $\Omega$  is then non unitary.

354 In the conventional version, quantum amplitudes (bra or ket) are associated with the states of a  
 355 system. It turns out therefore incomprehensible that the same physical situation (the cat + nucleus  
 356 complex) is simultaneously represented by a superposition and a mixture. Two "states" can not in fact  
 357 be superposed and incoherent at the same time. In this version, however, the amplitudes are associated  
 358 with events and not with states of any system; moreover, the nature of this association is different for  
 359 the superposition and for the mixture.

360 In the conceptual experiment of the cat, the superposition of amplitudes associated with the  
 361 nucleus (the "qubit") is relative to the two outcomes  $G$  and  $E$ , conditioned by past events (the

362 "preparation"), of an event that has not yet occurred. The conjugated superposition is relative to  
 363 the results, conditioned by future events (the "detection"), of a past event already happened. The  
 364 elements of the density matrix of the cat + nucleus complex (the "bit") are instead related to events  
 365 actualized in the present moment and to their logical negatives: the single nucleus is "already decayed"  
 366 (G) or "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 compared to the fineness of the quantum of action; on this level the possible non-commutativity of physical quantities does not therefore 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 therefore 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  $|\beta|^2 = 1$ :

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

367 Accordingly, in our re-formulation of quantum mechanics, the measurement apparatus is not  
 368 in a superposition of pointer states. Therefore, if the measurement apparatus and the micro-entity  
 369 undergoing the measurement are closed inside a box inaccessible to an external observer, who however  
 370 knows the initial state of the complex apparatus + micro-entity, this observer cannot legitimately  
 371 deduce that such complex is in a superposition state. In fact this is not the law of evolution of this  
 372 complex in our version of quantum mechanics. Therefore paradoxes such as that of "Wigner's friend"  
 373 can not arise, nor more elaborate paradoxes such as the one recently discussed by Frauchiger and  
 374 Renner [28,29].

### 375 5. Quantum jumps and bits: localization in time as information

376 In this section, in which we will allow ourselves to be a little more speculative, we would like to  
 377 reconsider the idea of 'event', understood as 'localization in time', from an informational perspective. It  
 378 seems to us that a possible starting point in this direction is represented by the uncertainty principle. In  
 379 our proposal, this fundamental principle of QM describes the intrinsic limitation of the manifestation  
 380 of physical quantities on a quantum scale (let us consider, for example, the a-spatiality already  
 381 mentioned in the case of the position). An expression of type  $\sigma(q)\sigma(p) \geq h/4\pi$  indicates that it is  
 382 not possible to reduce the product of the amounts of delocalization  $\sigma(q)$  of the position  $q$  and  $\sigma(p)$  of  
 383 the momentum  $p$  below the limit value  $h$ ; this value then sizes the volume of an elementary cell in  
 384 the phase space. The volume occupied by a physical system in its phase space therefore contains a

385 finite number of distinguishable states. The information associated with the manifestation of one of  
 386 these states is therefore finite, though it may be enormous. Bekenstein estimated an upper bound for  
 387 information  $I$  associated with a system with total energy  $E$  enclosed in a sphere of radius  $R$  in ordinary  
 388 three-dimensional space [30]:

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

389 The finiteness of  $I$  defines a range of *classical* values attributable to two non-commuting variables  
 390 such as position and momentum. An examination of the system on a finer scale leads us into realms  
 391 dominated by delocalization and entanglement, such as that of atomic orbitals and their transitions  
 392 [31]. On the other hand, a compromise between classical properties and quantum uncertainty can arise  
 393 when weak measurements are performed [32].

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

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

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

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

414 One can ask if there is no minimum proper time interval  $\theta_0$  between two successive temporal  
 415 localizations of the same particle. One can also wonder whether the coordination of events by an  
 416 observer is not limited within a horizon of radius  $ct_0$  centered on the observer itself ( $c$  is the limit  
 417 speed). We can attempt to estimate  $t_0$  from the experimental value of the cosmological constant  $\lambda$ ,  
 418 which is in the order of  $10^{-56} \text{cm}^{-2}$ . Assuming that the origin of such a constant is the presence of a de  
 419 Sitter horizon, the relation  $\lambda = \frac{4}{3c^2 t_0^2}$  must hold, which provides  $ct_0 \approx 10^{28} \text{cm}$ . The de Sitter horizon  
 420 area is then  $A \approx (10^{28} \text{cm})^2$  and inserting this value into (23) we obtain  $I \approx 10^{123}$ .

421 We can divide the portion of the contemporaneity space of the observer, internal to the  
 422 observer de Sitter horizon, in 'cells' of volume  $(c\theta_0)^3$ , each corresponding to a distinguishable spatial  
 423 localization. Since the radius of the horizon is  $ct_0$ , the number of such cells is  $N \approx [(ct_0)^3 / (c\theta_0)^3]$ .  
 424 Each cell can be in one of two states: 'on' if a localization occurs in it, 'off' otherwise. The number  
 425 of possible states is clearly  $2^N$  and the information associated with these states is  $\log_2(2^N) = N$ . We  
 426 assume that quantum jumps manifest the elementary components of the physical system within an  
 427 elemental cell of volume  $h^3$  in their phase space, so that each state will correspond to a cell of volume  
 428  $h^{3N}$  in the phase space of the total system. The logarithm of the number of states is therefore the same

429 information  $I$  of (23) and we have  $I \approx [(ct_0)^3/(c\theta_0)^3]$ . From this relation we obtain  $c\theta_0 \approx 10^{-13}cm$ ,  
 430 a result that is of the same order of both the classical radius of the electron and the range of strong  
 431 interactions (color confinement). The time interval  $\theta_0 \approx 10^{-23}s$  is of the same order of the 'chronon'  
 432 that Caldirola introduced, in his classical theory of the electron, just as the time interval between two  
 433 successive localizations of the electron in space-time [39,40].

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

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

## 450 6. Quantum computing in and beyond spacetime

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

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

457 This qubit will be by hypothesis associated with a particle. We also assume that the basic  
 458 amplitudes  $|+\rangle$ ,  $|-\rangle$  are spatially encoded, in the sense that the attribution of one of these two  
 459 amplitudes to the particle corresponds to its localization in one of two distinct spatial regions. We can  
 460 consider the actual case of a particle of spin 1/2 sent to a Stern-Gerlach analyzer which separates the  
 461 two components of spin along the direction of the applied magnetic field. The click of the counter "+"  
 462 downstream of the analyzer will be at the same time the measurement of the spin with result  $+1/2$   
 463 and the spatial localization of the particle within the volume of the counter. A similar consideration  
 464 will apply to the click of the "-" counter. Consider then a system of  $n$  particles, each associated with a  
 465 qubit with basis amplitudes distinct from those of all the others. By encoding each of these amplitudes  
 466 with a distinct spatial region, the total amplitude of the  $n$  particles will be a superposition of  $2^n$   $n$ -ples  
 467 of distinct spatial regions. While the quantum computing occurs at the level of the phase relations  
 468 between these  $n$ -ples, which are a-spatial and therefore not subject to any constraint of spatial nature,  
 469 the situation is a little different for the single  $n$ -ple. It is indeed evident that every  $n$ -ple of space  
 470 regions must belong to space, and therefore be contained in it as a subset. Now, the maximum number  
 471  $n$  of qubits with spatially codable basis amplitudes will be given by the maximum number of possible  
 472 spatial positions for a particle at a given moment, within the cosmological horizon. As we have  
 473 argued in the previous section, this number is  $I \approx 10^{123}$ . In other words, the number of qubits will  
 474 be subject to the Bekenstein limit  $n \leq 10^{123}$ . Naturally this limit is satisfied by all current and future  
 475 quantum computer projects. But it is also possible show that it is unreachable by computers made

476 up of ordinary matter with stable nuclei and electrons. The average density of ordinary matter in  
477 the Universe (with the exclusion of dark matter and dark energy) is  $\approx 5 \cdot 10^{-31} \text{g/cm}^3$ . Almost all of  
478 the mass is represented by nucleons, with an individual mass of  $1.67 \cdot 10^{-24} \text{g}$ . It is obtained hence a  
479 nucleonic density of  $3 \cdot 10^{-7} / \text{cm}^3$ . About half of the nucleons consists of protons and assuming that  
480 their charge is neutralized by as many electrons, an electronic density of  $1.5 \cdot 10^{-7} / \text{cm}^3$  is obtained. We  
481 have therefore a particle density of  $4.5 \cdot 10^{-7} / \text{cm}^3$ . Assuming a de Sitter radius of  $1.4 \cdot 10^{28} \text{cm}$ , there  
482 are therefore in total  $0.5 \cdot 10^{79}$  particles (nucleons and electrons). A lot less than  $10^{123}$ .

## 483 7. Comparisons with other approaches

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

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

508 Our description, therefore, does not contemplate the possibility of spontaneous flashes  
509 distinguished from ordinary interactions, but has instead to do with a quantum discontinuity connected  
510 with such interactions [31]. This point is relevant with reference to the measurement theory (see the  
511 conclusion of [47]). Moreover, we see no reason to favor the positional basis and we mean the  
512 localization in a temporal, not a spatial sense. What is instantiated is the projector on the quantum  
513 amplitude and not the spatial position. We see the peculiarity of the quantum description in the fact  
514 that, according to it, the ordinary interactions modify the amplitudes according to one or the other of  
515 two causal schemes that are mutually irreducible and, at the same instant of time, mutually exclusive:  
516 the unitary evolution and the QJ. To the dynamical causation (which involves the transfer of energy  
517 between spatio-temporal regions) a formal causation is added (which involves a certain localization  
518 information entering the spatio-temporal domain).

519 In describing both the relata and the relations, ie quantum jumps and transition amplitudes  
520 respectively, we have used their full temporal symmetry offered by the QM in its usual version. We  
521 have therefore considered both the transition amplitude and its conjugate and, for the QJ, both the ket  
522 and its conjugated bra. Both these choices recall the Transactional Interpretation of the QM (TIQM)  
523 introduced by Cramer in the 1980s [48–50] and advocated in particular by Kastner (see eg [51] for  
524 a general presentation of her views). As far as we are concerned, we have carefully considered the

TIQM since its appearance, letting us be inspired by its principles. However, we have developed these principles in a different form from the one originally proposed by Cramer [26,52]. Our personal elaboration naturally connects to the postulates presented in this article and clarifies them. However, it has led us on a path that differs from the TIQM for some significant differences, which we will now try to summarize.

The basis of transactional narrative is the simultaneous emission of the "offer" and its conjugated (the "confirmation"), respectively in the future and past light cone of the emission point. The same status of reality is attributed to the offer and the confirmation and the superposition of offers and confirmations induces the exchange of quanta. The emitter is therefore also an absorber, and the whole description is traced back to specific properties of the absorbers [53]. It seems to us that this description concerns the propagation of specific fields on the temporal (or spatio-temporal) domain and is therefore internal to this domain. It involves, even in the process of double emission or absorption-emission, the only efficient diachronic causality; that is, it has to do with a dynamical causality in space-time. In fact the reference model assumed by TIQM is the Wheeler-Feynman electrodynamics [48].

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

In this sense, perhaps the closest suggestion is the implicate order of Bohm-Hiley [54], however, with the important clarification that its explication occurs at the level of quantum discontinuity. As we have seen, informational considerations on discontinuity seem to connect in a natural way to two important scales: that of elementary particles and that of Planck, perhaps opening up new perspectives 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 [55–60]. 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:

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

For simplicity, we have considered only two (orthogonal) basis amplitudes  $s_1$  and  $s_2$  of  $S$  and two (not necessarily orthogonal) amplitudes  $e_1$  and  $e_2$  of  $E$ . Now consider the trace of  $|\psi\rangle\langle\psi|$  on the states of  $E$ ; it will contain terms of interference proportional to the real part of the scalar product of the two states of  $E$ . If the latter are orthogonal, the interference disappears, whereas in the general case it will be attenuated. Because  $S$  is randomly chosen among the elementary components of the macroscopic system, and this random choice determines the components of  $E$ , we have that the

573 possible existence of an interaction of this type between  $S$  and  $E$ , independent on this choice, leads  
574 to a quantum decoherence between the elementary components of the system. This decoherence  
575 makes the system, in a certain sense, "more classical" because it diagonalizes the density matrix of  
576 each of its components, averaged on the degrees of freedom of the others, on a basis selected by the  
577 interaction itself. Of course, coherence does not disappear, it is simply transferred from the basis  
578 elements of  $S$  to the amplitudes of  $S + E$ . This is the mechanism underlying the theory of decoherence.  
579 In our approach all this remains true. Now, however, at a given instant of time the total amplitude  
580 expressed by the preceding equation "collapses" into one of the basis amplitudes of  $S$  ( $s_1$  or  $s_2$ ) due  
581 to a quantum jump. The probability of the two results is defined by the diagonal components of the  
582 density matrix in the basis  $s_1, s_2$ . After the collapse, the off-diagonal coefficients reappear as a result of  
583 unitary evolution, until a subsequent quantum jump. Thus the *mean* density matrix will have both  
584 diagonal and off-diagonal terms. The decay of these latter in a "multi-hit" process (where each "hit"  
585 is a QJ) was analyzed by Simonius in a pioneering work [61]. The decoherence time is a function of  
586 the frequency of the Rabi oscillations of the free  $S$  system, of the degree of orthogonality between the  
587 amplitudes of  $E$  and of the (normally Poissonian) temporal distribution of "hits", in turn dependent on  
588 state variables such as temperature and pressure. The mean effect of a succession of quantum jumps  
589 on the evolution of the density matrix therefore seems to be what the theory of decoherence describes.  
590 From our point of view, however, the fundamental process is a piecewise unitary evolution, whose  
591 intervals are joined by genuinely non-unitary discontinuities.

## 592 8. Conclusions

593 As is well known, the absence of trajectories in quantum formalism and the instantaneous  
594 cancellation of the wave-function when the particle impacts on an absorber make any interpretation of  
595 Quantum Mechanics (QM), based on a realistic classical approach, extremely difficult. This difficulty  
596 has generated the two still dominant trends in the debate about the nature of QM. On the one hand  
597 the idea of the incompleteness of the theory, that goes back to Einstein and arrives to date with  
598 proposals like that of 't Hooft, on the other one the 'pragmatic' approach of Bohr that is centered on  
599 what the observer can say of the world through measurement procedures (for a good recent review,  
600 see [1]). It should be said that none of the two trends provides universally shared answers for the  
601 weirdest aspects of QM. We recall that the 'realistic' and 'pragmatic' trends have been established long  
602 before the experimental confirmation of non-local aspects. If, for the Copenhagen view, non-locality  
603 is an 'unexpected host', for realistic theories it is difficult to reconcile QM and relativity. Both of  
604 the interpretative lines have tried to retain the image of persistent micro-physical objects bearers of  
605 persistent properties. Realists used 'globules' driven by a medium, while pragmatists saw quantum  
606 amplitudes as descriptors of the 'state' of a 'system'.

607 Our re-reading of QM basic postulates identifies the 'quantum jump' with the notion of 'physical  
608 event', i.e. the temporal localization of a set of physical quantities, without any necessary relation  
609 with the measurement processes and apparatus. The causal connections between events is assured by  
610 the unitary time evolution of amplitudes, corresponding to a condition of temporal de-localization  
611 of those same quantities. This connection (if any) is probabilistic, and is described by the Born rule.  
612 No 'micro-object' is assumed in the time interval between two subsequent events. The quantum  
613 amplitudes associated with the preparation or post-selection are therefore not 'states' of any 'system';  
614 in particular, a linear superposition of these amplitudes has not to be intended as a superposition of  
615 'states'. Temporal localizations of physical quantities thus assume the role of primary elements of  
616 physical reality, with the result that the latter is made up of events, and no longer objects.

617 The Hilbert space thus becomes the basic mathematical structure that allows the definition  
618 of events as projection operators on the one hand, and the specification of the conditional  
619 probability of causally related events on the other. This approach eliminates the fundamental role  
620 of measurement-based notions (such as that of 'observable') while retaining the potentiality of the  
621 conventional formalism. Detaching the meaning of quantum mechanical formalism from the narrow

622 situation represented by the usual experimental setup with the stages of preparation, propagation  
623 and observation broadly extends the scope of application of formalism itself. The widespread use of  
624 formalism that has been made over the decades to describe the structure of matter (particles, nuclei,  
625 atoms, molecules, condensed states) is in this way justified.

626 The quantum jump is a non-unitary operation that converts quantum information (encoded  
627 in forward or backward amplitude) into classical information; operation which is represented by  
628 an appropriate projector of a Hilbert space. The QJ consists in the temporal localization of the  
629 physical quantities summarized in this projector. "Matter" is understood here as the complex of these  
630 localizations and not as some kind of support for localized quantities. Each QJ is an elementary  
631 interaction in the course of which a quantum of action is exchanged and therefore materializes a single  
632 elementary cell (bit) in the phase space of a physical system. An analysis of the cosmological limits to  
633 positional information associated with these localizations was carried out in Section 5. It is important  
634 not to confuse this information with that processed by a quantum computer, as the Universe or a  
635 computer that simulates it. The cosmological limits induced on this second information are analyzed in  
636 Section 6 and the results are congruent with the well known calculation of Lloyd [62]. A difference from  
637 Lloyd's assumptions is that the concept of "event", which is here distinct from that of "observation",  
638 does not in itself imply any irreversibility. As a result, most of the QJs are not registered.

639 Quantum information is processed between two successive QJs, causally connected through a  
640 transition amplitude. This processing does not "take place" in the usual sense of the term because the  
641 quantum superposition, considered in the time interval between the two QJs, is a pure mathematical  
642 construct (Section 2) that evolves only in the sense of its parametric dependence on the instant of the  
643 second QJ (forward amplitude) or first QJ (backward amplitude). Not surprisingly, the attempt to  
644 analyze this evolution in spatio-temporal terms leads to virtual trajectories joining virtual sub-events,  
645 for example the two paths in the double slit experience. These paths are naturally interfering and it  
646 has been argued that this is the origin of the hyper-Turing nature of quantum computing [63]. Taking  
647 this suggestion, an important field that opens to further investigations is that of the clarification of  
648 the relationships between the hyper-computational aspects of quantum computing and the non-local  
649 structure of elementary interactions modeled by quantum theories. Structure that seems to indicate an  
650 emergent aspect of the spatio-temporal ordering of events.

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