Quantum Mechanics *versus* Special Relativity:
A forgotten conflict

by

Professor Rafael-Andrés Alemañ-Berenguer

Group of Natural Philosophy and Scientific Metaphysics
"La Foia d'Elx" Institution c/Pr. Av. de Sant Andreu, s.n.
03294 - Elche - La Foia (Spain) 03015075@edu.gva.es

and

Dpt. of Quantum-Relativistic Theories
Astronomical Society of Alicante
Apartado de Correos 616, 03080-Alicante (Spain)
agrupación.astroalicante@gmail.com*

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[*] Any comment on this paper is kindly requested for it to be sent to this e-mail address

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Abstract

Despite the widespread assumptions on the compatibility between non-relativistic quantum mechanics and special relativity, there still remains a considerable amount of unresolved problems to which few authors explicitly pay attention. Most of them involve the aim of coherently achieving a relativistic description of quantum collapses and quantum entanglements. These processes seem to challenge our present picture of the physical world in terms of space-time structures.

Keywords: quantum mechanics, special relativity, quantum collapse, quantum entanglement, space-time, causation, separability, locality, non-locality, asymptotic independence.

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I. Introduction

The memorable experiments of Aspect in 1982 on the EPR paradox reinforced a controversy that was never entirely resolved: the presumed compatibility between Einstein’s theory of special relativity and non-relativistic quantum mechanics. The matter does not only concern the relativistic nature of the Dirac equation, an achievement that was regarded as a first step toward a more ambitious goal. It involves the apparently deep incompatibility in the global conceptions of the universe entailed in their very roots by the ontologic premises of both theories.

Just since the beginning, it was evident that quantum mechanics comprised elements hardly reconcilable with special relativity. Einstein's theory supported a geometric vision of space-time, in which past, present and future composed a unique structure whose combined perception was forbidden by the tridimensionality of our senses. In total opposition, quantum indeterminism, promoted and irreducibly random view of reality, and open to numerous future possibilities. However, if “future” is a relative term (according to Einstein, some future events for an observer can be present or past events for another observer), what physical meaning can we attach to quantum indeterminism? At most, it could be considered as an expression of our ignorance about the total set of events displayed in space-time. But this frontally collides with the interpretations that attribute an objective character to quantum probabilities. Special relativity, therefore, would seem to plead for the existence of hidden variables in a sub-microscopic level.

The obvious alternative to this posture would consist in denying the validity of the typically relativistic space-time description, whenever we enter the realm of quantum phenomena. The notion of a continuously divisible fourdimensional manifold for space-time, would be simply inapplicable in the range of sizes in which quantum effects become relevant. In essence, that was the Bohr's position, although he never clearly specified the concept that should substitute, on his view, the classic space-time.

In this essay I will attemptt to discern to what extent the epistemological implications of quantum mechanics and special relativity, drove to mutually-excluding conclusions on the nature of the physical world. Schroedinger was one of the most qualified authors that earlier approached the question in a clear and explicit way. To this discussion he dedicated the last two chapters of his book *The New Ondulatory Mechanics* [1]. The penultimate one, titled "Microscopic physics and geometry. The rigid body in the new mechanics", Schroedinger demolishes any hope of conserving, even ideally, something similar to the perfect rigid body of classical mechanics. In the literality of their words, he argued [1, p. 57]:

> "Absolutely rigid bodies do not exist. But classical mechanics did not prohibit to appeal to them. It allowed to invent forces or any potential energy among the material points that compose the solid bodies; which evidently allowed to come closer to the rigidity as much as wished. Nonetheless, there might happen, however, that the theory of quanta would make impossible the existence of an absolutely rigid body. If this were that way, it would be inadmissible to use it in a mental experience. The antitheses that we find when applying geometry to atoms would be comparable to the very well-known failures that are experienced in thermodynamics, if it is allowed to mentally operate with a body that is thermodynamically impossible. (...)."

Lackness of rigid bodies prevents us to specify without ambiguity notions that are basic for geometry, as those of consistency or longitude. Not having rules whose invariable longitude can be warranted, we cannot assure that two segments, for example, measure the same quantity. The application of geometric concepts to the atomic world becomes this way a very controversial matter.

It is even more complex, since the configuration of the intermolecular bonds involves the existence of quantum levels separated to each other by a finite quantity of energy. So, it will be always possible to break this connections giving them a quantity of energy that is also finite. Not even in the ideal limit we would ever have a perfectly rigid body, neither in the macroscopic domain nor in the microscopic one. The foregoing argument shows that we find impossible, even in principle, to conceive ideal experiments which could support the notion of punctual position, a concept that in turn endows the notion of point-like particle with physical meaning.

The situation is even worse when passing to the theory of Relativity, as exposed in the last chapter of the aforementioned book od Schroedinger, titled “Quantum mechanics and relativistic mechanics. The variable time.” Now, punctual positions are not enough, because we also need to fix instants in time to characterize with rigour a reference frame in space-time. Einstein itself was well aware of the difficulties provided that, as much in theory as in practice, observers carry out measure operations with rules and clocks (or some equivalent devices). When we try to adjust the march of a collection of clocks located in an ideal mesh as an extended coordinate system all over the space, it becomes unavoidable to observe them somehow, and more than once. If we get enough information of one of such clocks by means of a light ray sent forth from it, this emission produces an associated motion of recession. As a purely relativistic phenomenon, this displacement would cause a delay in the clock march with regard to us, external observers, besides the corresponding Doppler effect in the emitted light. All this was known by the first relativist experts who were not much too alarmed because they trusted in the possibility of imagining, in the limit of an ideal case, totally immobile bodies and clocks with perfectly uniform march, as everyone reasoned when classical mechanics held.

But there happens to be that quantum requirements prohibit us a similar escape. The pulse of light emitted by the clock and received by the observer, must be sufficiently brief in order to maximally accurate the instant to which it refers. However, the more brief it is the less monochromic the light pulse will be (a bigger amount of frequencies must be superimposed to narrow the wave package), and the less precise the aforementioned recession speed will be. All these effects will also reduce our possibilities to infer the alteration suffered by the clock during the process, and the precision of our time measurements will irretrievably decrease.

By means of semirigurous arguments, Schroedinger concludes that the limit of precision with which space-time events in a reference frame characterized by a mass m can be specified, is $\Delta t \sim h/mc^2$. After a similar reasoning, he deduces that the a rule calibration (the exact spatial location for the extrems of a longitude unit) can be achieved no more accurately than h/mc. Substituting m for the electron mass, the Compton wavelength is obtained ($\sim 10^{-13}\ m$), the one which –in Schroedinger's opinion– constitutes an impassable practical limit when using the notion of reference frame in the micro-world.

The brilliant Austrian physicist adds two supplementary argumentational lines to highlight that the reconciliation of relativity and quantum mechanics was a pending and thorny topic. One of them arises when considering what happens in systems with a perfectly determined mass (or energy), m. In such a case, the system would be in one of its stationary states, defined by the energy mc^2, and its wave function would be:

$$\Psi = \psi\,(\boldsymbol{q})\ \exp_e[-imc^2/\hbar], \qquad (1)$$

where $\psi\,(\boldsymbol{q})$ is the part that only depends on the position coordinates. The crucial detail is to notice that now the state function can split up in the product of an exponential function in which the variable t appears, and a factor independent of time. Developing Ψ as linear combination of a complete group of orthogonal functions (that is to say, a base in a Hilbert space), the absolute value of all the coefficients of this development will be independent of time. In consequence, anything happens in such a system, because anything changes with time; its dynamics, in brief, happens to be trivial or merely nonexistent.

In a second place, Schroedinger puts forwards a peculiarity of the time variable that got the attention of the first quantum physicists. A time-dependent wave function can show dispersion in all its variables except in time. Indeed, for the time variable a possible dispersion is not defined; that is to say, t lacks indetermination, in the quantum sense of the term [1, pp. 68-69]:

> "[The wave function] is considered as indicative of the system state in a precise moment, to the extent that all the other inherited concepts of the classic mechanics, except time, should change so that they do not mean a very certain thing in a very certain state of the system.
>
> This prerogative of time appears to be quite unlikely in itself. It is in contradiction, separately and independently, as much by the theory of relativity as by the known quanum-mechanical consequences regarding the existence of a precise clock.
>
> Since this last observation evidently shows an intrinsic contradiction with quantum mechanics, it could be expected that, once this defect is eliminated, the

> disagreement with relativity would disappear by the mere fact. But I believe that this hope is vain. (...).”

Schroedinger concludes with two very relevant comments whose better merit is to point directly to the heart of the enigma [1, pp. 67-68]:

> “By virtue of these considerations, the theory of the relativity is indeed relegated to the range of a macroscopic theory. At least we do not know yet their demands in a microscopic domain of space-time. I do not believe that these demands are translated in mathematical language in a so simple way as it had been believed up to now, that is: that the waveequations should be covariant under the Lorentz group.”

The precedent text contains the germ of two debates that, one century after having been written, still shake with overwhelming force the theoreticians’ minds. One of them is the proper transition from space-time as a macroscopic concept to what should substitute it in a range of ultramicroscopic distances, where the quantum strangeness puts in doubt our habitual geometric and topologic concepts. In addition to this, the last citation shows Schroedinger’s skepticims about the mere Lorentz covariance (just as it is imposed in the lagrangian or hamiltonian formulation of Relativity) as a sufficient guarantee for a deep agreement between the relativistic principles and those of quantum physics.

Schroedinger close his book with some deep-meaning words [1, p. 69]:

> "When demanding the precise adjustment of a clock, relativity itself is, neverthless, in contradiction with its own principles, combined with an experimental result.
>
> I find it very interesting that the two more important physical theories of the XX century both stumble with the same obstacle, and drive, both at two also, to suspect some kind of triviality of the variable time, that is in the base not only of physics, but of life too."

Everything worsened when experimental rehearsals confirmed the weird reality of the quantum non-locality predicted by Einstein, Podolsky and Rosen. If it was already very troublesome to combine the relativistic demands and the quantum ones in one and the same region of space-time, the difficulties for two regions spatially separate (they could not even be connected by means of a light sign) became overwhelming. From then on observations like Weinberg's echoed the thoghts of many researchers [2, pp. 78-79]:

> "(...) although not a theorem, it is broadly admitted that it is impossible to reconcile quantum mechanics and relativity, except in the context of a quantum theory of fields. A quantum theory of fields is a theory in which the basic ingredients are rather fields than particles; the particles are small energy clots in the field."

The purpose of appropriately combining quantum mechanics with special relativity, seems to require applying a series of conditions at first sight not very reconcilable among them; that is:

a) The dynamic evolution of quantum systems should be described in space-time terms, in connection with some inertial frame.

b) The transformations of coordinates between inertial frames should be those of Lorentz, in order that quantum states and their evolution laws remain invariant.

But the road toward the conjunction of both theories appears plagued of deceiving traps whose complexity is much deeper than what seems in a first analysis. Quantum systems, for instance, are represented by means of operators of density or state vectors (traditionally named "wave functions") in a Hilbert space, and their evolution takes place in that very abstract scenario. However, the Hilbert space does not keep a direct relationship, anyway, with our ordinary space-time in which the principles of Special Relativity are applied. There is not any form of obtaining the usual space-time as a limiting case of a Hilbert space.

In a second place –although not less important– we face the essential difficulty of conceiving the wave-function collapse as a physical process in a certain space-time frame. Diffraction experiments with quanta through a slit, are explained by means of the spatial stecthing of the probability width represented by the wave function. However, when an interaction occurs (let it be denominated "measurement" if wished) as the dimness of a concrete point in a photographic plate located after the slits, for example, the wave function gets instantaneously annulled –it collapses– all over the surrounding space. In the same way, a measurement on a member of a couple of entangled particles collapses the superposition and changes the state in the other component of the pair.

The dilemma is obvious: how can these collapses be expressed in terms of space-time function subject to he principle of relativity?; is their instantaneous and non-local nature acceptable in a relativistic context? The graveness of such question has inclined numerous authors toward an instrumental interpretation, focused on the utility of the wave function as mere device by means of which observers obtain the maximum possible knowledge from the observed system.

But this would take us to a subjectivist position that has no place in a physical theory rigorously formulated.

The simplest way out consists in denying the problem and adhering to a theory without collapse, modifying either the dynamics of the ordinary quantum mechanics [3, 4, 5] or even its ontology [6]. An additional merit of these two possible options rests in its ability to deprive quantum physics of its probabilistic nature. Indeed, on the one hand the Bohm dynamics is deterministic [7], and on the other the Everett interpretation of "many worlds" allows any result of a quantum experiment to be realized in some of its multiple universes.

With the purpose of completely understanding the whole problem, we will need to stop shortly on the reasons of this presumed conflict, also analyzing some of the proposals that were sought to solve it. Afterwards we will be in a better position to approach the foundations of the quantum field theories later on, where some of these problems vanish, although by no means they all disappear.

II. Objectivity of the "quantum collapse"

One of the postulates in which Von Neumann based its mathematical formalization of the nascent quantum physics is the reduction or "collapse" of the wave function. As we know well, it consists of a prescription that, when a measure is carried out, forces us to abandon the linear superposition of the various possible states of a microsystem, and to conserve only the function corresponding to the result obtained in fact in the experiment. To none of the first founders of quantum mechanics there were hidden that collapse was, with all evidence, a non-relativistic process. In principle the matter seemed to have scarce importance since Von Neumann's fomalism was also explicitly non-relativistic; the great Hungarian-American mathematician did not seek another thing in those moments.

A further and more careful analysis revealed that the reconciliation of relativity with this aspect of quantum physics, was much more delicate of what had been ingenuously supposed. The problem, surprisingly, got wrapped in the widest polemic on the problem of quantum measure. The confusion and the perplexities underwent by the intrepid cat of Schroedinger were themselves so astonishing that eclipsed the relativistic implications of the debate. But such implications, in spite of remaining unknown, subsisted closely bound to the indeterminism of quantum mechanics.

The unitary and linear dynamics, common to the ordinary formulations of the elementary quantum theory, does not provide us with the descriptions of the physical processes that would be expected from the point of view of our direct experience. The daily practice shows that experimental measures yield concrete and very defined results, and not a strange superposition of potential outcomes. It is generally admitted that the indeterministic character of quantum mechanics comes from the conjunction of two premises:

1. The state function ψ, does constitute a complete representation of the quantum systems (the eigenestates and the eigenvalues do configure the only description possible of such systems).
2. ψ always evolve in time obeying a linear dynamic equation

Such an embarrassing situation was summarized by Bell in a celebrated comment [8], according to which either the usual description of quantum states is not everything, or the unitary quantum evolution is not completely correct[1]. The growing interest in the non-linear quantum theories is justified for the wealth of possibilities that it offers in lines of research as quantum gravitation, theories of, algebraic representations and all kinds of fundamental speculations. However, it became soon evident that such formulations suffer, in origin, serious formal defects that make of their manegement a far-reaching matter.

The theoretical obstacles are very diverse, but maybe the most notorious one arises from the conflict with relativity (or, in other versions, with the principle of causation). It has been pointed out that the non-linearity in the quantum equations would allow us to use the EPR correlations and the instantaneous collapse of the state function, to establish an effective communication between events separated by an interval of space type [9, 10, 11].

A feasible solution would be to modify the algorithms associated to the measure processes, since the difficulty seems to reside in the instantaneous character of the state vector reduction, so the resulting non-linearity prevent influences to overcome the speed of light. Other authors, on the other hand, have argued that a hypotetical non-linear quantum dynamics is not itself the origin of these inconveniences [12, 13, 14]. Supposing that all the quantum measures are expresables, in the last term, as position indications, certain non-linear amplifications of the Schroedinger equation can be observationally equivalent to the linear equation after an opportune non-linear gauge transformation. Unfortunately, these reasonings are only applied in the non-relativistic case, and we are still very far from understanding all the implications from an appropriate extension to the dominion of relativity. Of all the theories without measurement collapse, the one that best fits for the relativistisc demands is that of the coherent histories, widely discussed in the specialized literature [15].

The situation is even more delicate when incorporating special relativity in the elementary quantum theory, because then we are deprived of the usual pseudo-operator of position. In 1949, T.D. Newton and E.P. Wigner published a well-known article in which they showed the practically unique characterization for a so-called “position operator” by means of its behavior under spatial displacements and rotations. However, the operator defined this way turns out to be non-covariant in a relativistic sense. Moreover, due to the positive sign of the energy in the ordinary physical systems, if in a certain instant we have an eigenstate of this operator (a "located state", in Newton-Wigner's terminology), after an infinitely brief interval of time the later state is extended all over the space. Such an unpleasant behavior has propitiated a plentiful literature about the discussion on the meaning and real utility of the concept of "localization" for a particle in a quantum-relativistic theory.

The truth is that in the usual relativistic versions of quantum mechanics, neither position nor duration are counted among the basic notions. The main role is played in this context by the quantum-field operator, that is parametrized by means of space-time coordinates regarded as classic magnitudes without dispersion (the "c-numbers" of Dirac).

Therefore, to solve the quantum problem of measurement implies to either reject one of those two suppositions (linearity and completeness), or alternatingly explain the disparity between our experience and the macroscopic superpositions to which the theory unavoidably takes us. In case we opt to suppress some of the two previous premises, we must make it under a global reassignment of meaning to the basic concepts of the theory that should be empirically correct and logically coherent at a time. Such semantic re-approaches are known as "interpretations" of the quantum physics, which, in spite of its vertiginous abundance, can be classified in three main groups [16, 17].

II.1. Objectivist Collapse

The first of them consist of the interpretations based on the objective collapse of the function ψ, and by this reason they are compealed to reject the assumption of a linear evolution for the state function. The dynamic equations are usually rewritten so they are sensible to certain value thresholds of the particle number or the mass density in a quantum system. When overcoming these thresholds the collapse of the state function takes place in a natural way.

The most developed proposal in this class (well-known as GRW theory) is due to Ghirardi, Rimini and Weber [18].

The GRW theory slightly differs of the quantum case in its predictions on the results of diffraction experiments and particle interference, although it also predicts little violations of the conservation of the energy. Experiences of neutronic diffraction carried out to decide the question [19], seem to lean for the ordinary quantum theory, in spite of which there are still plenty of researchers persuaded that some modification of this idea will provide the appropriate answers in order to get rid of the annoying collapse of the wave function [20].

Among these authors the American physique Wojcieh Zurek is counted, defending the so-called "environmentally-induced superselection". It is supposed that the immense quantity of degrees of freedom corresponding to the environment around any microsystem, is what causes the linear superposition of the quantum states described by the wave function of quantum to evolve quickly toward a unique state coincident with the classic result that in fact is observed. This way, for a mass of a gram, the interference terms of their wave function would diminish around 10^{431} times in a thousand millionth of second. This would explain why the typical quantum effects of the ultramicroscopic scale are not macroscopically appreciated. So seductive as it seems, the thorniest aspect in this alternative resides in elucidating the reason why the superselection eliminates all the less likely states, leaving only the one that in fact is experimentally detected.

II.2. Hidden variables

The second class receives the collective name, perhaps not very fortunate, of "theories of hidden variables" due to its negation of the first premise. It is supposed that the state function is not representationally complete –even when it evolves according to linear equations– and they what Bell denominated "beables" are added. That is to say, they are real and objectively existent physical entities ("beables") with independence of the observations and measurements that lie in the positivist language of the traditional quantum formulation. Everyone supporting the beable physics considers that the really existent things are particles or fields in the classic sense, for which it is prescribed a separate dynamics, as long as ψ contains the whole available information –always incomplete– on the micro-objects. Trying to overcome the classic meaning of "hidden variables", the modern modal theories supplement the description of quantum states with as many extra states as necessary to justify the obtaining of a concrete experimental result [21, 22].

Let us briefly remember the basic postulates of the alternative quantum theory elaborated by Bohm [23, 24]. One of them claims the existence of particles whose behavior obeys the prescriptions codified in their wave function. This wave function evolves in time and in the space according to certain equation (Schroedinger's, Klein-Gordon's, Dirac's, etc.). In the non-relativistic version the momentum of the bohmian particles satisfies the equality:

$$p \equiv m\frac{dX}{dt} = \frac{\partial S}{\partial X} \qquad (2)$$

where p is the canonical impulse, X is a point in the usual abstract space of the analytic mechanics, and S is the phase of the wave function. In the simplest situation, Schroedinger's equation and this last guide equation would be the fundamental laws of the microscopic world, on Bohm's view. Often A supplementary hypotesis called "distribution postulate" is added. Does this postulate consist in admitting that the density of initial probability is given by the absolute value of the square of the initial wave function $|\psi|^2$.

The physical interpretation did not go futher in the first works of Born [25, p. 804]. In them the wave function only refers to a probability wave that governs the particle motion, although this very probability spreads out in a causal and continuous evolution. The formal structure of Bohm's mechanics (here it is correct to speak of a true "mechanics" because the theoretical ontology posseses pointlike corpuscles among its primeval entities, and it can define positions and trajectories) maybe provides deep reasons to meditate on a possible privileged foliation in space-time. Just as we are given it, this theory is not covariant under Lorentz transformations. In the general case of a system with *n* particles, the guiding equation –the only distinctive dynamic law in this theory– involves the position of those *n* particles in a common instant for all, what presupposes the notion of absolute time. It is implicitly admitted this way a favored space-time foliation in spatial hyperplanes, which is, however, impossible to determine for all practical purposes.

It is not excessively difficult to build relativistic versions from a quantum theory in Bohm's fashion for a single particle [1, 26, 27]. The beable, in Bell's terminology, would be now the wave function of the particle and their trajectory would be the integral curve of a certain 4-vectorial field[2]. The truth is that any theory can be trivially made Lorentz-covariant, by adding all the additional structures that are necessary. There could be enough, for instance, including a privileged inertial frame as part of the specification for the quantum states. It seems evident, nevertheless, that strategy does not achieve a genuine relativistic covariance (understood this as the fulfilment of the proper geometric symmetries in the minkowskian space-time), although this is a very subtle and controversial question [8, 27, 16].

It is well known that the probabilistic interpretation of the Schroedinger equation for particles without spin, does not satisfactorily work when we try its direct relativistic generalization, the Klein-Gordon equation [28]. It is due to the fact that this last one contains a second derivative with regard to time, as distinct from the first time derivative that appears in Schroedinger's equation. We can no longer consider that the square of the wave function $|\psi|^2$ stands for the probability density of a quantum particle in an instant t, because then the total probability $\int d^3x|\psi|^2$ would not be conserved as time goes by. To introduce the preserved current $j_\mu = i(\psi^*\partial_\mu\psi - \psi\partial_\mu\psi)$ does not solve the problem, because the time-component j_0 cannot be regarded as a probability density in as much as it is not positive-definite[3].

The usual solution to this dilemma consists in pushing the theory forwards to the formalism of second cuantización [29], in which ψ is no longer a state-function that offers probabilities but a distributed magnitude –a "quantum field"– subjected to the Heisenberg inequalities. Nonetheless, if in a fundamental level $|\psi|^2$ should not be regarded as the probability density of quanta presence in a certain instant, it is hard to understand the reason why such an interpretation is in so extraordinary agreement with experimental data in the non-relativistic range.

Consequently it is not strange that some authors have attempted the coalition between Bohm's quantum theory [30, 31] and the theory of particle currents [32, 33], in search of a coherent combination of the postulates of the first one and the second quantization. In those tentatives it is tacitly supposed that Bohm's quantum theory possesses remarkable advantages over the orthodox interpretation in the relativistic regime, although the equations of the bohmian trajectories for the quantum-relativistic particles, described by wave-functions of many particles, are written in a way that seems to require a preferred time coordinate [34]. Because of this, there persists the doubt about the necessity of supplying with a privileged inertial frame, those relativistic theories of hidden variables that not seek to be at the same time compatible with the quantum locality [35].

II.3. Many worlds, many problems

The third competing group supports the idea of “many worlds” originally suggested by Hugh Everett III. This conception of a physical reality being unceasingly unfolded in countless separate ramifications, maybe, and only in certain sense, could escape from the problem of quantum measure seeking refuge in an interpretation of “relative states.” In this alternative form of expressing a stochastic process with several possible outcomes, the occurrence of all them is accepted, although locating those events in disjoint and mutually-excluding space-time regions [36, pp. 105-122.]. When the probability values are given by rational numbers, there is enough with a finite group of bifurcations in which the divergent universes differ in the realized outcome of some quantum process. In that case, a result whose probability is n/m will take place in n universes of a total of m unfolded copies. But situations characterized by probabilities that are irrational numbers, or stochastic processes with infinite different possible results (dispersion experiments, for example), would force us to define proportions among infinite groups, a truly thorny question [37, pp. 88-92].

Such a degree of incandescence has reached the controversy that some experts has even sustained in their writings the impossibility of building a realistic physical theory able to accommodate inside as much the quantum phenomena as the demands of relativistic covariance [38].

III. Troubles with space-time

The class of the objects to which the fundamental terms of a physical theory refer (whichever its ultimate nature can be) is denominated “primeval ontology” of the theory [45]. In classical physics, the place of this ontology was mathematically occupied by the material particles described by means of its world-lines. In the microworld we could imagine that classic particles are substituted by a continuous matter distribution related to the quantum wave-function.

But we could also suppose that the genuine essence of the quanta is better captured imagining them better as "flashes", or elementary events represented by isolated points in space-time [45, 27]. In a universe configured this way, the matter would be but an accumulation of flashes, and an individual matter piece would be a cluster of such space-time points.

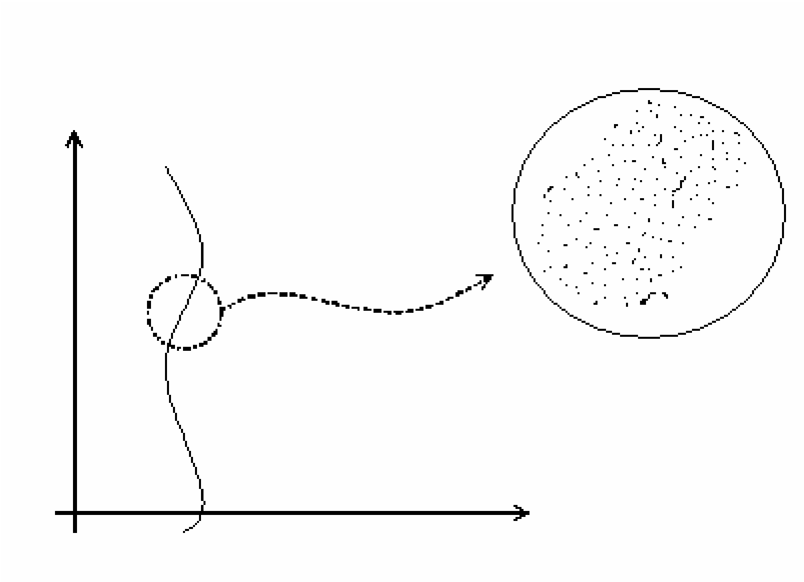

Figure 1.

The flash ontology is certainly a peculiar choice election, since in general world-lines or fields are usually taken to describe physical processes in space-time. The reason of this decision resides in the possibility of obtaining –with the opportune modifications in the equations– a model of spontaneous collapse based on flashes that it is also Lorentz-covariant. In a GRW model based on this idea, Bell flashes would form a random group of space-time points whose global distribution would be determined by the initial wave function.

The physical meaning of a GRW model that only accepts the existence of the wave function, on the contrary, involves serious interpretational problems.

The most obvious one is that we can hardly obtain a satisfactory description of physical reality by means of a theory that explicitly rejects to speak about the universe stuff. A theory like this would either judge unresolvable the problem of the matter existence, or establish so vague bonds between their basic concepts and the real objects-in the best in the cases-that almost anything could be said with sense on the question.

Let us sketch the foundations of the flash-ontology theories with GRW-collapses:

- The initial wave-function, in the instant $t = t_0$, is a unitary vector in a Hilbert space, $\mathcal{H}$.
- The flashes rate (the occurrence probability for a flash per unit of time) depends on the position r according to $\langle\psi|\ \hat{h}\ (r)|\ \psi\rangle$, where $\hat{h}(r)$ is a self-adjoint positive operator for all $r \in \mathbb{R}^3$.
- In a non-relativistic context with N distinguible particles, there are N different types of flashes, each one of them with an associated operator of speed, $\hat{h}_i$, $i \in \{1, 2, \ldots, N\}$. These operators of flash rates contain a gaussian function as a multiplicative factor:

$$\hat{h}_i(r)\psi(r_1,\ldots,r_N) = \frac{1}{\tau}\frac{1}{(2\pi\sigma^2)^{3/2}} e^{-(r-r_i)^2/2\sigma^2}\psi(r_1,\ldots,r_N) \qquad (3)$$

where the constant σ is the location amplitude ($\sigma \sim 10^{-7}$ m) and τ the time average between two collapses of the same type ($\tau \sim 10^8$ años)

- The hamiltonian $\hat{H}$ governs the evolution of ψ, when collapses do not happen.

It is interesting to point out that relativistic GRW-collapse models have been developed in a discontinuous space-time, construed as a reticle ($\mathbb{Z}_4$ instead of $\mathbb{R}_4$), contrary to the habitual continuous fabric of space-time.

We should not forget at al to ask if the quantum-physics interpretations that try to solve the measure problem, also entail a violation of the Lorentz invariance, destroying a possible compatibility with special relativity. If we conveniently restrict its meaning, Lorentz invariance would only affect to the dynamic laws that rule matter and radiation, not to the space-time structure itself. When understood this way, Lorentz invariance is not a space-time symmetry, but a purely dynamical one. And since the behavior of matter and radiation in different frames obey the Lorentz transformations, this point of view is empirically appropriate. However, the lorentzian theories of this kind suffer from a serious formal defect, because they happen to be unable to rigourously reflect space-time symmetries as much as special relativity does. Paraphrasing Einstein, we could say that on this view we find theoretical asymmetries that do not seem to exist in the phenomena. This is the main reason why mere logical economy invites us to abandon the Lorentz vision in favor of Einstein's.

If all this was problematic, more confusion still causes to insert in the debate those atypical readings of the Lorentz invariance, denominated "hyperplane-dependent theories". When we accept the validity of these unusual formulations, any of the foregoing quantum interpretations would be entitled to be judged invariant under the Lorentz transformations.

The equivalence –or covariance, if preferred– of the physical laws in all the inertial frames, as it is notorious, constitutes one of the basic presumptions in the special theory of relativity. To connect the expressions of these laws among different inertial frames, the rules are in fact the Lorentz transformations. From a rigorous point of view, the Lorentz transformations manifest the geometric symmetries of the Minkowskian space-time, symmetries that in turn exclude all the physical processes that do not obey them. To say it otherwise, when applying a Lorentz transformation we transfer our world perspective from a certain inertial frame that splits space-time in a spatial 3-surface and an associated time axis (that is a space-time foliation), to another frame also inertial with their own space-time foliation.

It is necessary, anyway, to highlight the practical differences among the space-time view of a concrete observer, and a tetradimensional foliation associated to this observer. It is true that an observer can be located in any physically-accessible frame of reference. And so it is that every frame is accompanied by a foliation consistent of hyperplanes orthogonal to its time axis (or, say it, to the observer's world-line located in that frame). The traditional pedagogic stories in relativity (with illustrations concerning to observers in trains or, nowadays, in spacehsips) take a risk to transmit the idea that the observers have access to all the points that form their associated spatial hyperplane in each instant. In fact, observers lacks information about events that are not in the region that should be denominated their “causal past” (or their “past light cone”). Those observers do not maintain a privileged relationship with events causally alien to them, although those events are in their orthogonal space hyperplane[4].

Neverthless, it is well known that in the vicinity of space-time regions where a collapse of the wave function takes place, it is impossible to properly apply the Lorentz transformations. Purely and simply, we cannot carry out a transformation from a simultaneity hyperplane where the collapse is a future event, to another hyperplane with regards to which that collapse is in the past. Only rejecting a distinguished tretament for this special points –the collapses– the difficulties are avoided. Otherwise, the transformations must apply to finite segments of the world line of a quantum system, segments that now can also include a collapse of the wave function. Even so the cost is high, because the quantum-state collapse instantly occurs in each hyperplane of simultaneity associated to every inertial frame.

The acceptance of the strict Lorentz covariance depends on our conviction that the symmetries underlying the relativistic space-time should be also respected by quantum mechanics somehow. Of course, it might be a wrong assumption. But in absence of any opposite prove, we should admit that relativistic requirements have always been satisfied in nature, which in turn increases the expectations for them to be satisfied in the micro-world, where quantum effects become dominant.

Regarding to this, the key of the controversy rests in the impossibility of establishing a privileged inertial frame. And if such a preferred frame does not exist, in certain sense the statements realized for an inertial observer should be essentially equivalent to the statements for any other inertial observer. This does not certainly mean that the states of one physical phenomenon is identical, point to point, in all the inertial frames; we already know that it is not this way. Relativity only imposes that in different inertial frames the values of this states must be related to each other by means of certain coordinate transformations (that is, the Lorentz transformations).

Attempts to solve the mess stipulating a privileged foliation in relativistic space-time of Minkowski would muddle the theory with asymmetries not reflected in natural phenomena. And a remarkable improvement is not possible when adopting the point of view of the GRW theory. Becuase here there is also a preferred space-time foliation, in as much as the collapse dynamics of ψ is not Lorentz covariant [38]. Nonetheless, the GRW theories of second quantization predict occasional violations of the Lorentz invariance, tiny but observable, what would allow to choose a privileged reference system.

The profile of the future quantum gravitation, still too rudimentary being in their first babblings, neither supply us with a lot of help. Some of these theoretical outlines seem to support the possibility of a favored foliation, while others (as loop quantum gravity) works without similar tricks. But it is also certain that none of these theories is fully developed; most of them lack of enough tools to be able to predict something, and others (the topological quantum field theory, for example) nor even possess a physical notion of “local interaction”.

The symmetry of the Hilbert space, on the other hand, allows to express a state function in any of the possible functional bases (position, energy, momentum, spin, etc.). A function Ψ that is written as superposition in a certain base, dos not have to be necessarily expandable as linear superposition in another different base. For example, a state function that turns out to be eigenfunction of the spin operator in the X axis with eigenvalue –½, will be generally expressed as a superposition of the eigenfunctions whose eigenvalues are + ½ and –½ in the Z axis.

Consequently, if we attribute an objective physical reality to the collapse of the state function, we must decide in which base it takes place. A comfortable choice (but not logically necessary) is the base of positions, as it is done in the GRW theory, what would suppress the superpositions of macroscopic estates in other bases. However, this would not eliminate the superpositions in bases associated to different operators: the eigenstates in the position representation, say it, correspond to those that are not eigenstates in the momentum representation.

The difficulties become worse when we try to couple the views about the time variable that we are given by special relativity (there is not a genuine and unique “time flow”; the events form series –world lines– causally connected in the Minkowskian space-time) and quantum mechanics (objective probabilities are assigned to events supposed to be randomly impredictible). To ease the comprehension, let us assume that in an instant *t* a radioactive atom has, according to our computations, a probability equal to 0,5 of disintegrating in the next period $t + \Delta t$. However, such an statement makes objective sense only if in the instant t there is not a future prefixed by the Minkowskian geometry of the special relativity. On having a complete 4-dimensional picture of space-time where that very atom gets disintegrated twenty-four hours after t, the propensive probability as an objective feature of the physical phenomenon should not be 0,5 but 1. Besides the non-local EPR effect, this is another key of the conceptual –although not empiric– incompatibility among both theories: if special relativity pleads for a static image of space-time, at the same time it disables the assignment of objective and non-trivial probabilities to quantum processes [39].

We would be tempted to adduce to this respect that this theoretical annoyance only arises adopting certain interpretations of chance, specifically the propensive interpretation of Popper about probability. Or conversely, admitting the absence of a time flow, we might consider that the impossibility of obtaining information about future events safeguards the objectivity of probabilities [40]. It may be this way, but it dangerously takes us to the controversy on the incomplete character of the state function and their nature as a proper physical entity in itself (instead of taking it like a mere calculation tool, as Bohr and their followers thought). Neither can we forget that most of the researchers have avoided these philosophical debates because of their suspicious taste of "metaphysics" involved with abstruse and never-ending questions about fatalism and predestination [41]. Maybe for that reason one can think that even submerged in an atemporal reality, in the sense of Minkowski, quantum probabilities do possess an objective meaning, as long as the space-time geometry of relativity did not mine our convictions on free will.

The answer to this dilemma doesn't seem so simple if we think of a couple of observers A and B just as special relativity describes them. Supposing that B moves with regard to the radioactive atom so that the disintegration has not occurred in his reference frame, his plane of simultaneity allows him to assign it a disintegration probability equal to 0,5 in the instant *t*. But if A moves in an appropriate way, his simultaneity plane will intersect the world line of the radioactive atom in the future of B. Then, for A in the instant *t'* the atom will be either intact or disintegrated, and A will assign, therefore, a probability 0 or 1 to each event. Everything indicates, apparently, that A and B will not coincide in the probability distributions attributed to the same phenomena, even when its inertial reference frames are perfectly equivalent from a relativistic perspective [42, pp. 204–212, 233–234; 43, pp. 298–303; 44, pp. 593-595].

Told in a more technical language: we know that every inertial frame selects a spatial hyperplane of simultaneity in the Minkowskian relativistic space-time. And we also do know that in each one of those hyperplanes the state function ψ define a probability distribution $\rho_\psi = |\psi|^2$. But if a privileged hyperplane does not exist –to uphold the notion of “absolute simultaneity”– and since in the different calculations carried out in different simultaneity planes will generally not agree, on which of them must we evaluate $|\psi|^2$?

The theoreticians, as we may have expected, did not stand quietly before such a defiant challenge. Bell himself felt very deeply disturbed by the question and he proposed the aforementioned “flash ontology” [45, 27, 46, 47, 48, 49, 50]. Thanks to this new ontology one can build a relativistic version of the GRW theory. The price to pay consists in losing locality: the wave function collapse, in spite of being Lorentz-invariant, is not local (that is to say, it violates the Bell inequalities). Nevertheless, the pursued objective is achieved: the relativistic-GRW version of the Bell flashes shows that it seems possible to reconcile a realist quantum mechanics with special relativity.

In sum, the dilemma for the scientists that support a realistic philosophy of physics through the quantum controversy, is presented as the necessity of choosing between two alternatives:

- Either they slightly modify the predictions of the usual quantum theory (according to the requirements of the GRW proposal or some other realistic version of the quantum theory),
- Or we all should change our ideas about special relativity accepting a privileged space-time foliation, what immediately drives us to the Bohm tracks for quanta in the relativistic space-time.

IV. EPR Correlations and Relativity

At the end of the XX century a significant series of experimental tests pointed out the existence of unequivocal correlations among spatially separated events in a relativistic sense (events non-connectable by means of light signs). Since such experiences were based on a discussion on the conceptual foundations of quantum theory suggested by Einstein, Podolsky and Rosen, it seems natural to abbreviate the denomination “non-local quantum correlations” as simply EPR correlations. Quantum physics explains them implicitly appealing to a preferred space-time foliation, what seems to exhume the ghost of the absolute simultaneity. It is true, for instance, that the original theory of Bohm is not a relativistic one as long as it requires a preferred reference frame for its dynamics [51]. But, on the other hand, the empiric Lorentz-invariance is preserved, in the sense that no possible experiment can determine this privileged frame [26, 52]. And it is also true that Bohm’s theory does not specify a probabilistic dynamics for the supplementary variables (or “hidden variables”), contrary to their field-theoretical extensions [23].

What has been often considered the distinctive stamp of the quantum theory, is the fact that any couple of initially independent systems, S1 and S2, can constitute “entangled” states, $S_1 \oplus S_2$. In them, the component subsystems lack an eigenstate vector, and the probabilities assigned to pairs of measures on each system are not factorizables as it would be for the product of two separate probabilities corresponding to each subsystem. This class of states was described by Schrodinger [1, p. 555] as “the characteristic feature of the quantum mechanics, the one that forces to a complete estrangement of the classic lines of thought.”

The entangled states conserve their character of such even when the spatial separation arbitrarily increases among the two subsystems. It has been experimentally proven this way even with photons separated by more than ten kilometers [53]. The empirical evidence compels us to admit beyond all doubt that physical objects located in different parts of the space cannot be considered entirely independent each other [54, 55]. It implied an authentic shock for our common ideas about physical causation, and resuscitated the secular philosophical debates on the nature of reality. Einstein expressed this way it [56, p. 215]:

> “If we wonder what is characteristic of the ideas of the physical world, independently of the quantum theory, the first answer is this: the physical concepts refer to a real external world, that is to say, it includes ideas of things (bodies, fields, etc.) that claim a “real existence” independent from the subject that perceives them, and these ideas are put in relationship (as sure as possible) with the impressions of our senses. A second characteristic of these physical things is that they are conceived as arranged in a continuous space-time.”

In another text, the German genius insisted on the matter [57, pp. 186-187]:

> “On the other hand, it is characteristic of the physical things to be conceived as being as arranged in a continuous space-time. Also, it seems equally essential for this ordination [...] that these things demand an independent existence one of the others as long as they are in different regions of space. [...] The relative

> independence of distant objects in the space (A and B) is translated into the following principle: an external influence on A does not have an immediate effect on B; this is known as the principle of local action that is applied consistently only in the ondulatory theory. The complete suspension of this principle would make impossible the idea of the existence of (quasi-)closed systems and, therefore, of the establishment of laws empirically testable in the usual sense for us"

Few times there has been exposed with so much clarity by one of the big creators of the XX century physics the philosophical background of their ideas. And in the case of the German genius their exposition is transparent: the basic structures of physical reality would fall inside the conceptual outline that attributes a finite number of invariant states (energy, electric charge, entropy, etc.) to physical objects that –ideally, at least– would be perfectly located in space-time. In Einstein's opinion, the natural world is analyzable in individual elements conceptually distinguishable, all them with the same ontologic category. The complex physical systems would consist, therefore, of organized structures, composed of those fundamental ingredients that are their constituents. It seems beyond doubts that Einstein essentially leaned on a monist ontology, in the sense of being based on a unique class of real objects, be either pointlike particles, continuous fields or any other entity to further elucidate [58, p. 104].

A realistic interpretation of quantum physics accepts that its basic theoretical entities –as the state function– are not mere calculation instruments, but they rather possess physical genuine reality whose existence is independent of the observer perceptions. This way, quantum mechanics would offer us an objective description of reality, even when the physical magnitudes often possess distributed values, instead of being precise arithmetic quantities. Exactly the same we could say about the probabilities and the quantum-state transitions, regarded as objective and not simple mental creations of the observers.

Classical physics, certainly, has always adhered to the four typical demands of the realistic philosophy [59, pp. 121-125]:

R1. **Substantiality**: Permanent identity of the physical things.

R2. **Physicality**: All existent objects are liable to be inserted in the physical outline of nature.

R3. **Accessibility**: Physical objects can be known, thought in a partial, inexact and always perfectible way.

R4. **Existential independence**: The physical things existence is autonomous with regard to the environment (intelligent observers, other physical objects, etc.).

To refuse the (R1) and (R3) premises would suppose in practice to forbid all possibility of rational discussion about nature; that is the reason why we will not insist in them. On the other hand, the requirement (R2) has been traditionally confused with that we can call, for want of a better term, *locationability*; that is to say, that all objects possess a concrete localization-–"point-like", we would say– in space and time. The quantum theory rejection to the locationability is certain, but somehow it also abandons physicality. It simply happens that the quantum outline of the world is radically diverse of the classic one, although in itself it is not less real. Finally, (R4) is the one that bigger controversy has generated, as long as the experimental outcomes on EPR correlations have been erroneously interpreted as a negation of it. Observers test the probabilistic distributions forecast by the quantum theory, and those experiments are fulfilled with no relation to the observers. The experiments test the probabilistic distributions but they do not create them anyway.

From a rigorous empirical point of view, it is certain that EPR phenomena does not allow to send faster-than-light signals [60, p. 453]. The relativistic postulates, therefore, are safeguarded in practice, although it is already more doubtful that they are equally respected in a theoretical sense. That the quantum EPR correlations cannot be managed to established effective communication between two observers was demonstrated as a theorem in 1980 without having been refuted from then on [61]. In fact, it is only necessary to open the discussion about possible quicker physical interactions that the light in the quantum level, presupposing –against the own foundations of the quantum theory– that photons in the Aspect experiment possess, each one separately, a state of well defined spin before the measure.

To understand the problems that non-local quantum correlations set up for relativity, let us imagine the space-time descriptions two inertial observers make of the same EPR experience. The observer A in motion, for example, toward the experimental device, would consider –according to their simultaneity plane– that the measurement on the first photon compels the second photon to jump to a spin state correlated with the first one. On the other hand, the second observer B, who moves away from the experiment, will reasonably claim that the second photon spontaneous collapse to a defined spin state produces the measurement outcome that happens later for B. The question is not of little importance, since if the two observers are physically in an equal foot, the space-time perspective of B introduces a flagrant violation of the quantum postulates: the spin state superposition of the second photon spontaneously collapses without external influence. And do both space-time descriptions differ on which event is a random result (a spontaneous collapse of ψ or a measure-induced collapse), and which ones is a result of the correlation.

For the sake of the forthcoming arguments, we will properly discuss the characteristics of this surprising not quantum non-locality. We can begin noting that physical systems are composed of two main elements: the laws that regulate their changes and the boundary conditions (data of the system in an initial instant or its behaviour in a well-known case) that allow us to apply this laws in a specific situation. The ideas admitted without doubts in classical physics from Newton on, sustained that in the behavior of a given system the influence from the remote parts of the universe is worthless. This leads us to the following statement:

***Principle of Asymptotic Independence*:** It is always possible, at least in theory, to sharply divide the universe in distinguishable parcels that, separated to each other by sufficient distance, do not interact in a significant way.

This principle implies that the *lex naturae* do not contain effects independent of the distance; that is to say, as two objects moves far apart from each other, its mutual influence continuously decreases until being completely annulled at an infinite separation. It is very important to highlight that this prescription only concerns to the evolution laws of the system. Although the Laplacian mechanicism does not know any other more physical influences than those that weaken with the distance (gravitation and electromagnetism), nineteenth-century scientists knew very well that such influences are only annulled at infinite, and for that reason it would be necessary to know the effect that exercises the rest of the universe on our system to determine the boundary conditions with perfect accuracy. That is why the old mechanicists needed to add an additional postulate that establishes the worthlessness of a little variation of the boundary conditions on the behavior of an arbitrarily distant system. That new principle is the “insensibility” to the boundary conditions, and therefore it doesn't concern at all to the evolution laws. The combination of these two principles, asymptotic independence and insensibility, leaded in classical physics to the systems that we would call "detachable."

The appearance of quantum physics on the scientific stage overthrew the first postulate and the coming of the chaos equally did with the second one. The EPR correlations introduced in the evolution laws effects apparently independent of the distance, as long as chaos brought the so-feared sensibility to the boundary conditions. It is of capital importance to notice that both prescriptions are logically independent, as it is demonstrated by the fact that there is a purely mechanicist physics (with neither quanta nor chaos), quantum physics without chaos (although there are already ongoing studies about quantum chaos) and non-quantum physics of chaos.

We can pay attention to finer details and to add new stipulations concerning the behaviors and states of the micro-objects studied by quantum mechanics. Let us add other two more postulates that will be of utility in the next discussions.

Principle of Isolation: Those physical systems liable to be isolated from their sorroundings are characterized by states that (1) have completely determined their locally-dependent features, and (2) the collective state of several systems are built by simply combining their individual states.

Reasoning this way, the liability of isolation is an ontologic hypothesis that we adopt as postulate without mentioning the spatial separation at all. We know many instances of quantum entanglement where it is obvious that there is not spatial separation –in the sense relativista of the term– among the parts of the global system. The collective spin state for two electrons in the fundamental state of an helium atom, is a singlet state although the electrons are not spatially separated.

Principle of Local Interaction: All interaction forces among physical systems are transmitted with a finite speed always inferior to that of the light in vacuum, *c*.

This principle is but an application of special relativity to the concrete case of the fundamental forces. No physical signal can be transmitted faster than light, and this restriction also extends to interactions of any fundamental force. Certainly, all the scientifically known interactions satisfy this requirement, what is as much as saying that physics excludes phenomena able to contravene special relativity. Let us notice that in the last postulate exposed above nothing is stated on the process, continuous or discontinuous, by which the forces spread. In the usual discussions the Bell theorem together with conditions of isolation and of local interaction are merely denominated "locality." The separability (strictly nonexistent in the non-linear dynamics) is regarded as a given fact, because here the linearity of the quantum theory basic equations is not questioned, neither the asymptotic independence of any two micro-systems.

A careful analysis of their foundations shows that quantum mechanics does not infringe the principle of local interactions at all, but does break the condition of isolation, as it is obvious in the entangled quantum systems. We are heading, clearly, to choose between two alternatives:

- Only one state function exists ψ that represents the non-local states of a quantum system as a whole, and whose form evolve wheter the states are measured or not.
- There are diverse ψ each one of which can be considered either an objective description of the system (what takes us to the many-worlds interpretation), or an expression of our subjective knowledge of their

states (what straightly pontis to an idealistic interpretation of quantum mechanics).

As all that we know up to now indicates that the collapse of ψ depends on the reference frane in which is contemplated (what clearly infringes the relativistic invariance), a possible way-out would be to admit the prevalence of one of these two opposite descriptions. Either the observer A or B –regaining the previous example– possesses the correct physical perspective; only one "watches" –to say it plainly– what really happens. The inconvenience of this option is that it favors one of the reference frames with no decisive reasons for it. Why must we grant priority to the observer A that see the first photon measure before, over B observations?, and what if there really happens a previously spontaneous collapse (something not considered by the usual quantum theory) that induce the measurement outcomes in EPR experiments?

This essential conflict with the relativistic postulates was immediately recognized by giants of the XXth century physics, as Dirac who said on the matter [62]: "it is contrary to the spirit of relativity, but it is the best thing that we can make. (...). We cannot be satisfied with such a theory." On the contrary, the conflict between a quantum world view and a relativistic one does not occur when choosing the second option about state functions. If we adopt a different ψ for every observer, the collapse is now conceived as a mere formal construction, a pseudo-event that takes place when the observer's knowledge about the system changes [63]. Only when we attribute objective features to ψ and demand that its collapse should be consistent with other physical laws settled down in a unique universe, do the paradoxes arise. However, neither this option lacks of disadvantages. On the one hand, the many-worlds interpretation presupposes the limitless validity of the usual quantum theory in all the distance scales, a hypothesis that is at least chancy. And on the other hand the subjective interpretation of ψ drag us –as it has already been said before– to an idealistic conception of quantum phenomena that has scarce relationship with the convictions and real practices exhibited by the members of this research field.

The EPR correlations should not be understood as a mysterious action at a distance that simultaneously concert changes among separate systems. On the contrary, the transformation of a global detachable state is not in itself an unitary transformation (although their constituents are spatially distant) in the states separated from the component parts. The principle of local action (that presupposes the asymptotic independence asintótica) constitutes a restriction on the possible alterations in the states of separated physical systems[5] [64, pp. 210–215; 65; 66, chap. 16]. In our case, the discussion on faster than light (FTL) effects at a distance only arises when we give stipulate, against the premises of quantum mechanics, that each quantum possesses a well defined spin state prior to the measure [67, pp. 115–117].

Now let us try to obtain a foliation in the Minkowski space-time that should be also acceptable for an appropiate description of quantum processes. To this aim, it seems indispensable to satisfy a series of conditions:

- All the physical processes must be described as a succession of states contained inside that foliation.
- No foliation should be privileged in the sense of containing the only correct series of states.
- The differences among series assigned to different foliations must be entirely attributed to the fact that the diverse foliations compile the space-time points in a different way, and according to this way the simultaneity hypersurfaces in which are defined the quantum states are also arranged.

- Once given the complete series of quantum process states in a certain foliation, the homologous series (corresponding to the same process) in other foliations are uniquely specified.

The third condition perhaps seems to suggest some kind of system isolation, in the sense previously enunciated, but it is not that way[6]. It is enough to impute the differences among the different foliation states to local events, that is, events confined to the region among these hypersurfaces[7]. This last detail can be also explained appealing to the algebraic language of the quantum theory of fields. In that context we usually associate to each open space-time region, O, an operator algebra, $R(O)$ whose selfadjoint members correspond to the observable magnitudes by means of operations[8] confined to that region O. Given two disjoint enclosed regions, O_1 and O_2, the physical processes in the region $O_1 \cup O_2$ are generally not uniquely determined by indicating the values of all the local magnitudes in O_1 and O_2 –magnitudes represented by operators $R(O_1)$ and $R(O_2)$– that possess definite values. We must also specify the values of the magnitudes represented by operators in $R(O_1 \cup O_2)$.

Let us take as example the singlet state of two quanta with spin ½. The unique specification of such a state is achieved imposing the annulment for the sum of both spins in anydirection; the total spin is always zero. In this case it is not possible to appeal only to the individual spins in order to obtain a good characterization of the singlet state. Similar description of the quantum state, consequently, violates the aislabilidad condition. Simply it is not true that the behavior of all the objects in the physical world should be deducible starting from local states belonging to points or to minuscule enclosed regions of the space-time.

Despite all this, let us suppose that for every space-time foliation we have a series of states that embrace all the physical events along the successive hypersurfaces that constitute that very foliation. The challenge would be now to accommodate the notion of “state function collapse” in such a picture of reality without sacrificing, among the conditions before enumerated, neither the second (there are not privileged foliations that give the only correct series of states) neither the third (the differences among the series of states contained in diverse foliations are entirely due to the fact that different foliations locally rearrange the series in a different way). Equivalently, the question is: can the collapse theories satisfy, or not, conditions of local evolution preserving at the same time an acceptable notion of quantum probability[9]?

According to the ideas defended by Aharonov and Albert [68], in every foliation the state function collapse happens in the hypersurface that contains the event that we call “measure”, or in general, “interaction.” The suggestion is reasonable: we suppose that the collapse happens in a certain closed[10] space-time region Ω. If Ω is in the future of a certain hypersurface Σ, the state function in Σ will represent a superposition without collapsing. When Ω is located in the past of Σ, the state function in Σ will already have suffered the collapse. What would happen to the state function in a surface that just intersecte the region Ω is a more delicate question that depends on the concrete details of the collapse process. A similar conception, although restricted to the spatial hyperplanes, resides under Gordon Flemming's proposal and in the works of those who strongly wish to get a relativistic version of the localization continuous models or instantaneous collapse [69, 70, 71, 20, 72].

A crucial ingredient in this construction is the objectivity of the quantum probabilities whose values seem to be different in every reference frame and also to evolve with time. In any instant t, there exists a random function, P_t, that assigns a certain occurrence probability to each possible event, in the past, present or future. The probabilistic distribution P_t corresponding to a time *t*', after t, is obtained imposing on P_t conditions dependent onf the complete series of system states[11] between *t* and *t*'. The idea seems to be physically reasonable at first sight; but, is it feasible in the real practice?

In a Galilean space-time, with a distinguished foliation thanks to the absolute time concept, the computation of the interim states between two given instants lacks of ambiguity. In a relativistic context, however, given two points A and A' on the world line of an object, how to select the events on which the stochastic function evolution depend in order to obtain the appropriate probabilities of the different events in the future of A (among them A' itself)? It is not clear, for example, if we should include the events (which ones?) spatially separated from that whose probability we try to calculate. Anyway, for every spatial hypersurface Σ, we will have a probability distribution P_Σ conditioned by all the events belonging to the past of Σ. This is the reason that we need to specify the spatial hypersurface to which we refer when we seek to calculate the probability of a certain state in a system *S* inside a certain space-time region Ω. Or, in other words, it is indispensable to know on what events our conditional probability depends (that is just why it is named “conditioned”).

The EPR correlations supports the idea of a probability conditioned by spatially separated events. Being this way, we can hardly reject in principle the idea of conditioned probabilities depending on future events, with the advantage that such a feature would offer us a much more complete picture of the evolution for quantum states on the spatial hypersurfaces that configure every possible foliation. For example, let us take again an electron pair, e_1 and e_2, whose spins undergo a measurement that yield one of the two possible outcome, +½ or –½. Be Σ the spatial hypersurface that intersect the world line of e_1 and e_2 in the past of this measure, and Σ' another hypersurface that is in the past of the measure on e_1, but also in the future of the measurement on e_2. Then, from the perspective of Σ the probability of each spin value is 50%, while from the point of view of Σ' these probabilities will be 0 or 100%, becuase for the latter the measurement on e_2 has already happened and therefore the e_1 spin has got a well defined value.

As stranger as it seems, it must be this way, because the specification probabilities from Σ' is conditioned by the whole past of Σ', what also includes the measure realized on e_2. Contemplated this way, there is no longer a paradox involved in the fact that a quantum measurement can be stochastic from the perspective of a certain hyperplane, although it is also deterministic from the point of view of another one. The reason for this astounding result is that the probabilities assigned for the same events, depend in each hyperplane on different groups of space-time events [42, p. 209.]. In our case, the probabilities calculated for Σ are spatially conditioned by separate events (the measure on e_1 affects to e_2, and vice-versa, no matter how far apart they are), as long as those of Σ' does not depend on that class of events (the e_2 outcome is in the past of the measure on e_1, and will not be affected by it).

The ordinary quantum dynamics teaches us that a state vector in an instant t_1, $u(t_1)$, evolves to a vector $u(t_2)$ in a later instant, t_2, by means of the Schroedinger equation. The use of sentences as “instant t_1” or “instant t_2”, implicitly presupposes a certain reference frame with regard to which we specify temporal durations. In consequence, when expressing the wave function in the base of position states (what provides us the density of probability for the presence of the quantum particle in diverse regions of the physical space), the state of the quantum particle in an instant t with regard to a frame f, will consist of a defined probabilistic distribution on a simultaneity hyperplane of f. In anotherframe, f', we will have other probability distributions in their own simultaneity hyperplanes, related with those of *f* by means of the opportune transformation equations.

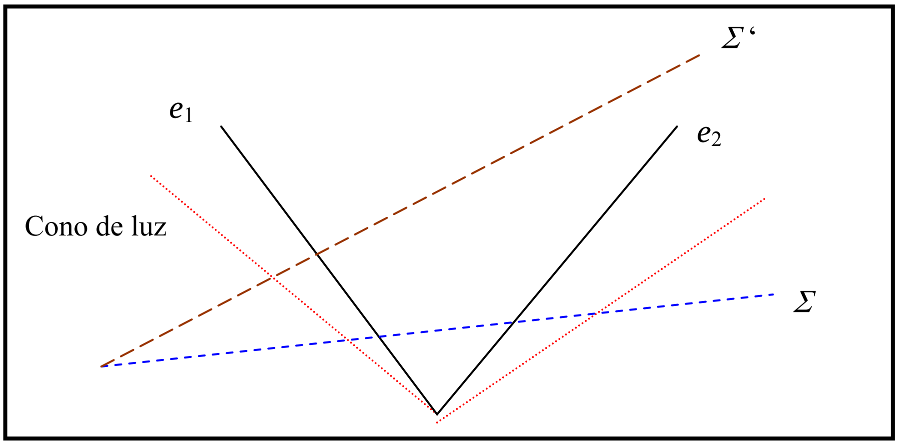

Figure 2.

An elaborated model of state-vector reduction exists, due to Fleming [71], in accordance with which the spin values of the photons in the EPR experiments are considered relative to a certain reference frame, or more accurately, relative to a specific spatial hyperplane [42, pp. 204–212, 233–234; 43, pp. 298–303; 73, pp. 593–595]. But, whatever their strengh be, these proposals have the virtue of illuminating a central question in our controversy: the search of a reconciliation among the quantum non-separability and the relativistic locality forces us to consider the states affected by quantum entanglement, not as intrinsic features of the micro-objects, but as relational states (that is to say, states that acquire meaning in connection with something external to the object that possesses them).

Let us take a further step and analyze, in the light of the precedent discussions, the relationship eigenstate-eigenvalue stablished by the elementary quantum theory. It is generally admitted that a certain property represented by an operator $\hat{w}$ will possess an eigenvalue ω_k if, and only if, the quantum state $|\psi\rangle$

satisfies the equality $\hat{w}|\psi\rangle = \omega_k |\psi\rangle$. Taking a local neighbourhood in space-time, Ω, that contains a system or a physical object liable to be in the eigenstate $|\psi\rangle|$, we face two possibilities: either the eigenvalue ω_k depends on the hypersurface that contains that neighbourhood Ω , or it is an absolute property, only dependent of Ω, and not of the hyperplanes that contain it. Obviously, if we want to establish local and intrinsic states for the physical systems, we should appeal to the second alternative. Ghirardi and their collaborators [74, 75, 20, 76] made this way and proposed that a system in a space-time point *P* possesses an objective property (that is, only dependent of the local neighbourhood, Ω, just as it was said before) expressed by a certain eigenvalue ω_k if, and only if, the system state in its last cone of light is a eigenstate of the operator $\hat{w}$ whose associate eigenvalue is in fact ω_k.

This notion of defined property, in the sense of Ghirardi, fits well to the idea of world line of an object or system in space-time. Nevertheless, the concept of an hyperplane-dependent property is also useful in other situations. Both conceptions possess their proper application fields, and therefore to inquire which of them capture the true essence of reality, is unsound. The authentic relevance of this distinction resides in avoiding the confusion among both notions, remembering that the dependence with regard to the spatial hypersurface does not attribute intrinsic states to the physical systems.

Incidentally, we might have the solution of the perplexity exposed in the previous section. There we saw that different reference frames in relative inertial motion would assign different probabilities for a measurement outcome to the different points of a quantum particle world line, considering if the simultaneity planes associated to every frame are in the future or in the past of the measurement. This is that way, indeed, and with it the propensive interpretation of probability is deprived –at least in a context relativista– of its great attractiveness. We can no longer consider that quantum probabilities are inherent states to a microphysical object, as electric charge or spin, but features partially dependent of the space-time frame chosen for their description. Such a conclusion is not in itself a tragedy, but certainly it will darken even more the endless discussions in this respect for epistemologists and metaphysicians.

From what has been said we can infer that it is not legitimate to expect a strict ontologic compatibility between special relativity and quantum mechanics. EPR correlations, for example, prevents us to suppose that the premises of both theories are fully reconcilable without difficulties. In fact, we experienced that quantum systems, in general, respect neither the principle of parametric independence nor the principle of isolation, in spite of which violations of the relativistic requeriments never occur. So we reach our second conclusion that is the existence of a "dynamical compatibility" –if we decide to call it this way– among both theories in conflict. This dynamical compatibility is given as much in Collapse quantum theories as in those that work without it. And in both cases, the relativization of quantum states according to the spatial hypersurface wherethe observer is, seems to be the natural way of extending the quantum non-locality to the relativistic domain. In spite of everything, it is still a wide territory to explore in the search of an entirely satisfactory combination between the quantum mechanics and einsteinian relativity.

We would need to guarantee the appropriate covariance of Ψ when transforming among inertial frames, of a rule to calculate the transition probabilities, and of an evolution equation for Ψ (except, maybe, during collapses). And when Ψ were an eigenstate of a certain operator, the probability of obtaining its eigenvalue should be equal to 1. Can we define then a complete set of conmutable operators using the space-time symmetries of the Lorentz transformations? If the answer is negative it will not be possible to define the physical state of a system by means of the same eigenfunction for all those operators. Once again, the source of the major ambiguities is the freedom of the different inertial observers to define its own spatial simultaneity surfaces. With it, in each inertial frame we will obtain different probability distributions for the same quantum process.

The debate has ended up being so intricate that some authors had been leaded to consider it a not well outlined question[12]. In their opinion, it cannot exist a quantum relativistic theory that is not also, rigorously speaking, a theory of fields. Hence there would not be an intermediate stage between the non-relativistic quantum theory and the quantum theory of fields, understood as the incorporation of the relativistic requirements to the quanta behavior. However, as to whether this opinion is a good response for the collapse problem, is another controversial question. It is deeply doubtful that quantum field theories –at least in their present state of development– would consistenlty answer the questions here formulated[13].

V. Factorizability and causation

In the Bell inequalities, when applied to photon pairs with correlated polarizations, it is supposed that for one photon the variables on which the probabilities depend, are irrelevant in the calculation of the probabilities associated to the other photon. This supposition was formally translated in the "factorizability condition", which, roughly exposed, consisted in the possibility of decomposing the state function of of the photonic pair in the product of two independent functions, each one of them belonging to one of the separate photons.

The discussion on the true physical meaning of the factorizability condition, matured definitively after the analysis of probabilities carried out by John P. Jarret for EPR photons [77]. His work concerned two experimental variables: the choice of the magnitude to measure and the obtained result. Their idea tried to prove that factorizability implied the conjunction of two independent premises with different physical meanings. If only one of them is directly linked to special relativity, the non-fulfillment of the factorizability condition could be imputed to the violation of the remaining premise. Hence, the EPR correlations would be compatible, in principle, with the relativistic demands [78, pp. 445-455; 79].

After logically disectioning the factorizability condition (that he also calls "condition of strong locality"), Jarret extracted two basic principles. They were denominated "weak locality" and "completeness." These requirements received with posteriority the names, respectively, of "parameter independence" and "outcome independence[14]". If applied to a couple of entangled quanta, the parameter independence would guarantee that the probability of obtaining a certain outcome when measuring the polarization of one quantum particle, does not depend on the orientation of the polarizer that measures the other particle. The outcome independence –when satisfied– would establish that, whichever the physical magnitude measured in the quantum pair is, the probabilities of the possible experimental results for one member are not influenced by the measurement outcome of the other one.

The accumulation of sufficiently reliable experimental data invites us to think that the infringed rule is not the parameter independence, but the outcome independence [80]. The likeliness of this conclusion grows when remembering the consequences of the superposition linearity in the quantum states. For a quantum pair, one of them is in fact the impossibility of discriminating, when there is entanglement, the individual state of each particle. From a physical point of view, such a violation of the outcome independence is regarded as the most outstanding expression of the "non separability" of certain quantum states. Moreover, when the parametric independence is not satisfied, it would be possible to establish some kind of effective communication faster than light between the couple of correlated particles [81, pp. 91-109].

Before the discovery of quantum entanglement, it was tacitly admitted that all connections among physical phenomena located in different places, was liable to be accounted for in two ways: either a common cause that originated the correlated behavior existed or a direct interaction occured among them (so to speak, a causal chain that directly goes from one to the other). As the measure in an EPR experiment is carried out when the particles are already separated traveling in opposite directions, it seems reasonable to discard the common cause and to concentrate on discussing the direct influence. And here it is where the analysis of our suppositions on the causal propagation in physics would play an essential role, as long as we want to know how much the quantum entanglement respects the relativistic constrictions.

Figure 3.

Hans Reichenbach (1891-1953) was one of the eminent thinkers that dedicated his efforts to elucidate the bases on which our ideas about the physical causation in nature are sustained [83]. In their opinion, the notion of causal propagation is founded upon three crucial conditions that would be [84, 85, 86]:

I. *Continuity*. The causal processes that relate the events that we denominate "cause" with those that we denominate "effects", are continuous in space and time.

II. *Condition of Markov*. The future behavior of a system, knowning its present state or its evolution during a certain time interval, do not depend on its previous states. In other words, the way in which a cause C has taken place is irrelevant in its influence on an effect E.

III. *Time asymmetry*. The relationship cause-effect is chronologically asymmetric, because the cause always precedes in time to the effect ("time precedence"). Therefore, it is always possible to determine the time order of two events causally related.

The hypothesis I, referred to the causal continuity, is in the root of the approach called "mark criterion" –also proposed by Reichenbach–according to which the structural modifications suffered by a system due to any interaction, are generically denominated "marks" [84, chap. 23]. Hence, a causal process would be able to transfer marks from some physical systems to others through space and time. How such a transfer wouldhappen? The idea consists inn imagining a process P without external interactions that would conserve a characteristic Q uniformly along a space-time interval whose ends would be two different events A and B. Then, when in the point A a unique interaction that converts the characteristic Q into Q' happens (the mark), the process P transmits this mark to the point B if Q' is manifested in B, as well as in all the intermediate points supposing the absence of all external influence.

The search of an explanation for the EPR correlations, just as they spring from the violation of the Bell theorems, drove us to reject the hypothesis of a common cause, implicit in the factorizability condition that –as we already know– is not fulfilled. Consequently, the only alternative seems to be the existence of a possible influence that infringes the local causation, just as it is concieved in the relativistic space-time.

But, focusing on the entangled couples used in the EPR experiments, are they really separated? Before we urge ourselves to respond “yes”, we should meditate on how many different matters are involved in that question. Few doubts are that in scales comparable to the Planck lenght (about 10^{-35} m) our geometric concepts, and even the topologic ones, must be gravely overturned by the quantum fluctuations of the own space-time fabric. It is very likely that such ideas, and with them all our vision of reality, should suffer a dramatic rearrangement. David Bohm thought that way when he exposed his ideas on the “interconnected totality” in diverse books and articles. On his view, below the apparent chaos of the quantum chance a deeper level underlies in which the basic structure of nature appears as a continuous and indivisible totality. The quanta that are supposed to be distant from our macroscopic point of view would be in fact a partial blooming of that final structure which would remain submerged, so to speak, in a subquantum level still to explore.

Bohm did not specify very much the idiosyncrasy of such a unitary entirety. Hence, his proposal, interesting as it was, got relegated to the diffuse domain of unmatured physical ideas. However, his writings left us very attractive metaphors in this respect. According to the analogy of an hologram (record of a three-dimensional image on a two-dimensional surface, whose individual fragments contain information able to reproduce the complete image), all portion of the universe establishes a net of relationships with the rest that would allow it to react before the occurrence of certain phenomenon no matter how distant it is. This researcher pointed out that, although the division of the world in a great quantity of apparently autonomous objects has been key in the development of our understanding of the reality just as it is expressed in the classic science, this image is essentially erroneous when a deeper description of the ultimate reality is pursued. Remembering the platonic myth of the cavern, Bohm argues that the objects and the rules that are fleetingly shown to the physicist scrutiny, are something similar to the projections in a smaller dimensionality than of a world with a higher number of dimensions.

This bond between a super-dimensional reality and the world that reveal our perceptions, is gorgeously captured in the television spectator's example and the filmed fishbowl. Bohm suggests us to imagine what a spectator would reason when watching two televisions, each one of them retransmiting images of the same fishbowl but focused from two different directions. Although there is not more than one fish, the figures contemplated by the incautious televiewer would seem totally different. However, with some patience and a sagacious observation, it would not take long for the viewer to discover a perfect correlation between the movements of both images. The observer would face a clear dilemma: either admiting that that stranger agreement constitutes an unresolvable paradox, or supposing that the screens show two-dimensional images of a three-dimensional reality. Of course, from the last point of view the correlation lacks mystery. Bohm judges vry likely that the EPR correlations and other paradoxical aspects of quantum physics, point toward that ignored subquantum world.

With similar intention, Reichenbach uses the appealed example of the two-dimensional inhabitants located on a sphere surface [85]. Let us imagine these curious beings becoming obstinate in the statement that they live on a plane surface, even when their measures of angles and distances indicate them the opposite conclusion. It would not be difficulty for them to modify their physical laws, introducing specific forces and material states that affect their measure instruments. So those two-dimensional beings could justify the discrepancy among the inferences deduced from their measurements (they inhabit a closed curved plane) and their own intellectual prejudices (they live on an infinite plane surface).

Such a procedure leaves aside the vital importance of the purely topologic properties that as well characterize the existent diversity of spaces and surfaces. The sphere, for instance, is a closed surface that can be surrounded walking straight on until arriving once again at the starting point. If we call *A* the departure point of the itinerary, the two-dimensional beings that always advances ahead without deviating to one side or to the other, would end up reaching again the point *A*. Obviously, something like that would be impossible in an infinite plane surface, and the fact that it happens arises as a serious inconvenience for the thesis of the plane world. The only excuse for the two-dimensional creatures would consist in declaring that the point at which they arrive is not really the original point *A*, but another different point, *B*, that is completely identical for some special reason to *A*.

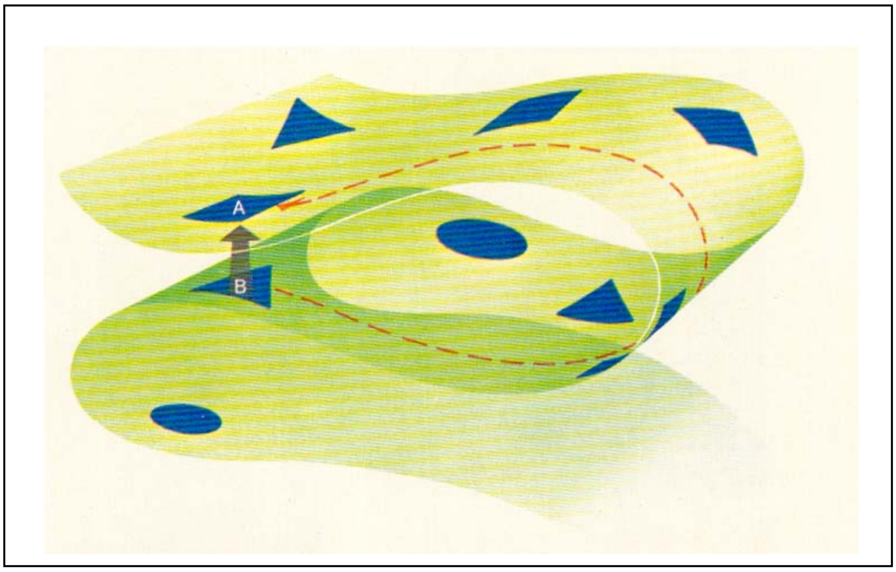

Figure 4.

The residents of the spherical surface, therefore, can opt to either admit that their existence takes place on a spherical surface, or cling to the idea of the plane inventing some theory that explains why *A* and *B* are identical in all the aspects, in spite of being considered different and spatially separated points.

Even it may happen that then the two-dimensional creatures adopt the belief in some kind of pre-established harmony: all that occurs in *A*, instantly occurs in *B* as well.

Reichenbach sustains that this last alternative involves a suspension of the causation just as it is conceived in the physical science. If we accept the rules of the ordinary causation –as they have been enunciated before– the topology is shown to be able to reveal us the global geometric characteristics of the physical world. Otherwise it is unavoidable certain degree of ambiguity in our geometric deductions about spaceas a whole; it would be always possible for us to use a plane geometry altering our notion of causation at the same time. Therefore, the result that Reichenbach judges more important in the precedent analysis of the epistemological implications of topology, claims that the choice of certain theory about the physical space depends on our decision on the preservation, or not, of the ordinary causation rules. We can overwhelmingly adhere to a certain conception of space, paying the price of giving up the ordinary causation. And, otherwise, we can also conserve the principle of causation in their habitual formulation, losing the freedom of arbitrarily choosing the geometric description of space.

The relationship that all this keeps with the EPR paradox is immediately obvious. Just as the two-dimensional beings that get surprised by the identity between the points *A* and *B*, we feel perplexed when finding distance-independent correlations between separate physical objects. Just as they trust an illusory "pre-established harmony", we arrange doctrines on "the things that only exist when measured" or those "faster than light actions at a distance" to remedy our ignorance. And maybe in both cases the true solution rests in an eased mind opening before more radical redefinitions of the physical world[15]. Perhaps what we believe elementary particles spatially separated, are but superficial manifestations of physical entities to elucidate. Maybe our space and time notions are deducible in some sense from those entities. In spite of their high degree of abstraction, these entities would finally correspond to those "elements of reality" that Einstein, Podolsky and Rosen mentioned in their celebrated paper. They would be pre-geometric ingredients that would appeal to a genuinely primeval structural level deeper than those of "space-time event" or "quantum state." It has been indeed the aim of all those that attempted, at the end of the XXth century, to deduce the space and time concepts (and with them those of distance and duration) from some sort of underlying elements. And although their efforts were not crowned by success, the road remains open for those who want to accept the challenge.

VI. Some discussions

There have been attempts to prove that the intriguing conflict between the special relativity postulates and the quantum-mechanical collapses can be explained as the same process accounted for from different reference frames. This point of view claims that entangled systems undergoin collapse are not problematic if we are given the proper refrerence-frame choice and the correct interpretation for space-time event arrangement. Unfortunately, the things are a bit more complicated than this optimistic explanation could make us believe.

Let us take Wayne Myrvold's paper as an excellent representative of this class of responses [86]. He begins his work with a good summary of the confonted opinions expounding as well in detail the arguments stated against a relativistic-covariant account of quantum collapse. Afterwards, he reaches the core of his own answer:

> "... The state defined on σ_p is entangled, whereas the sate defined on σ_p' is factorizable, even though the two hyperplanes intersect Particle 1′s worldline at the same point *P*. This circumstance, a consequence jointly of the relativity of

> simultaneity and of modelling collapse as a local change in the sate vector, can with justice be called the relativity of entanglement." (86, p. 449)

But indeed this reply is not a legitimate one. The key of the problem is just that: we cannot construct a coherent world picture if two hyperplanes intersecting a unique worldline at the same point produce two different states, one entangled and one not entangled, for the same physical object. Hence, nothing is gained whether we claim that the problem has vanished after covering it with a very impressive name like "relativity of entanglement". Provided that "entanglement" and "non-entanglement" are two incompatible ontologic categories, we are not allowed to ascribe them to the same space-time event (and to the physical entity attached to it).

The misguided argumentation continues ahead in the text saying:

> "There is therefore a form of holism associated with the quantum-mechanical description of composite systems. (...). The relativity of entanglement can be regarded as one manifestation of this relational holism." (86, p. 455)

Of course, if there exist a sort of relational holims in quantum mechanics is certanly not involved with that presumed "relativity of the entanglenment", which happens to be only another new name for the same unsolved problem. Moreover, Myrvold adds a surprising comment:

> "... Insofar as there is a wave function at all, whose square gives a probability density for the location of a single particle (and this must, ina relativistic context, be regarded merely as an approximation), it is a foliation-relative object: not a function mapping spacetime points onto numbers but a functional taking both a spacelike hypersurface and a point on that hypersurface as arguments (...). There is no contradiction, therefore, in the claim that the

> collpase of the wave function is simultaneous with respect to every reference frame and, in general, with respect to any foliation of spacetime into hypersurfaces of simultaneity." (86, p. 463).

Despite those confident asserts, a careful consideration shows that there is a true contradiction, because in every foliation spacelike hypersurfaces define orthogonal timelike vectors in order to assign different time parameters to every (hyper)plane of simultaneity. In consequence, what is a wave-function collapse in one foliation is not compeled to be necessarily a collapse as well in another foliation.

Strocchi [87] critically analyzed the basic features of quantum relativistic mechanics in connection with questions concerning the foundations of quantum field theory. Hence, he did not directly touch the collapse problem but offered very qualified comments:

> "It is a common belief that (non abelian) gauge theories provide the way out of the triviality theorems, but again a non perturbative control is lacking; moreover (...), such theories involve strongly delocalized (field) variables (typically those carrying a non zero charge), whose quantization requires either non regular representations of the canonical commutation relation (CCR) or a violation of positivity by their vacuum correlation functions. In both cases, the quantum mechanical interpretation of such variables is not standard." (87, p. 502).

VII. Conclusions

In summary, great part of the confusion about the role of space and time in quantum physics, could have been dissipated distinguishing between the space-time coordinates (that are *c*-numbers) and the dynamic variables (inherited from analytic mechanics through the hamiltonian formalism) that characterize the space-time behavior of physical systems. Since quantum particles are not reducible –not even ideally– to point-like corpuscles, an authentic "position operator" does not exist in quantum theory, and neither there is a "operator time." The opposite, and very common, belief is founded in a double mistake: on the one hand, to confuse the dynamic variables of position, typical of the corpuscles, with the mathematical coordinates of points in space; and on the other, to assign the dynamic variables of position to physical entities, as quantum particles, for which they are essentially inappropriate.

When we try to submerge quantum mechanics in a relativistic formulation, the requirements of space-time covariance become so demanding that we are even deprived of the resource to an improper "position operator": the concept of pointlike object gets lost *ab initio* even in a much more transparent way than in the non-relativistic quantum theory, and the entirety of the controversy turns obsolete.

Above all, a coherent relativistic account of quantum collapses seems to be a non-achievable aim if we cling to the standar interpretation of both special relativity and quantum physics. Quantum superpositions, entanglements and the so-called "reduction of the state-vector" are not liable to be described in terms of the Minkowskian space-time symmetries (the Poincare group) and their associated geometric structures. This is the rrot of the confrontation between the two major physical theories in the XXth century. We may hope that XXIst century will find out the ultimate solution for this question and for many others also involved, even though now we cannot imagine how.

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session of the Astronomical Society of Alicante, I was given very interesting remarks when this paper was presented for general consideration

Notes

1. Everett's many-worlds proposal does not come into this dichotomy becuase in this theory the quantum description is supposed to be complete and unitary evolution correct. An interesting discussion on that matter appears in [17].
2. For example, the currents naturally associated to Klein-Gordon's or Dirac's equations.
3. This does not involve any difficulty in the dispersion formalism, where it is admitted that the wave functions asymptotically behave as plane waves of positive frequency. Nevertheless, quantum mechanicss is much more than the mere theory of dispersions, and the problem of the negative values of j_0 reappears out of the dispersive range.
4. In fact, for a given space-time point P we have a multitude of "presents" to choose, each one corresponding to the diverse hipersurfaces that contain P. Therefore, the idea of a present spatially extensive and independent of an arbitrarily chosen foliation fails. An idea that is, although defective, detectable in a numerous amount of philosophical discussions yet.
5. The causal processes would be those that possess and transmit a conserved physical magnitude, and in turn an interaction would be globally an exchange of such conserved quantities.
6. A "local"observable is anyone which can undergo local observations (reducible to an as small space-time as neighbourhood as it is wished). A global property (which, at least in some cases, is not reducible to an arbitrarily small region), on the contrary, will be, so to speak, the mass center of a mass distribution spatially extensive defined on a hipersurface

Σ. This property is assigned to a point in Σ, and for that reason we say that it is located inside Σ, although this claim is not inferred from local observations in the previously described sense (in delimited space-time regions that contain that point). Certain authors [88] have adduced that the Newton-Wigner position operators are placed in the same way without being locally definable.

7. The ordinary presentations of the quantum theory –by means of Heisenberg's picture– tend to forget this circumstance. Translated to Schroedinger's picture, we obtain series of states in hipersurfaces that evolve according to the Tomonaga-Schwinger equation.
8. Kraus [89] argues that any physically possible interaction (with a strongly positivistic jargon, he speaks of "physically realizable operations") can be symbolized by a positive-definite linear mapping φ (a "cartography") of the group of the traceless operators on itself. It also demonstrated that all function φ is expressable in terms of a numerable group of operators, $\{K_i\}$, the Kraus operators. This way, the Kraus representation of the usual unitary evolution, consists of an only unitary operator of Kraus.
9. Here, the word "acceptable" implies the execution of the non-signaling theorem. Henceforth, EPR correlations allow to neither send signals faster than light nor establish simultaneity relationships at a distance.
10. "Closed" in a topologic sense: the border points also belong to the set.
11. It could be objected that all those "histories" (complete series of states) of a system between two given instant, do not constitute an infinite numerable group. In itself it would be impossible –at least with the usual definition of probability– to assign a non-null probabilístic value to any individual history. This dilemma has two outways: either we alter the

ordinary notion of conditional probability, or we establish appropriate restrictions on the domain of our probability function of. See an interesting discussion of the alternatives in Lewis [90], pp. 263–293.

12. For example, Malament [91] claims to have elaborated a theorem that proves the impossibility of building a “quantum-relativistic mechanics of localizable particles” without simultaneously including physical influences (no EPR correlations) faster than light.
13. We can say little about superstrings and M-theory becuase they are so incompletely defined –in an epistemological and even technical sense– that it is hardly possible to clarify an accurate delimitation of the problem in these theories
14. Alternatively, other authors distinguish between“ontologic locality” and “sorrounding locality”, such that the second one presupposes the first one. An interesting exposition is offered in Redhead [92].
15. The topologic notion of multiply-connected spaces as base for different quantum theories goes back at least up to 1950 [93, 94]. The path-integral on multiply-connected spaces made their entrance in Schulman [95] and Laidlaw & DeWitt [96]. To deepen in that subject, it can be also consulted Schulman [97]. And in many of these works the question of the multivalued scalar wave functions is as well approached.

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Figure captions

Fig. 1. Pictorial image of the “flash ontology”, as a group of individual points in space-time

Fig. 2. The hyperplane Σ intersect world lines of e_1 and e_2 in the past of their respectivemeasurements, but Σ' has e_2 in its past and e_1 in its future. The lines of reddish color symbolize a light cone in space-time.

Fig. 3. Hans Reichenbach.

Fig. 4. Two plane inhabitants of a surface curved in a third dimension would feel very far away according to its conception of reality, although they are very close from the perspective of the additional dimension that they ignore.