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Nonlocality in Everettian Accounts of Quantum Mechanics

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Abstract

In this work we investigate the problem of locality in theories inspired by Everett's Relative State Theory. Specifically we address the Many Worlds by Deutsch, the Many Minds Theory by David Albert and Barry Loewer and the Relational Theory by Simon Saunders, and we carry out our inquiry in view of recent work by Meir Hemmo and Itamar Pitowsky. Our aim is, on the one hand, to clarify the remarkably important points which have been put forward within Hemmo and Pitowsky work on the issue of the interpretation of probability in Many Minds, on the other hand to argue against a remark on the Relational theory, stating that the analysis carried out on the Many Minds interpretation could be applied, *mutatis mutandis*, to Saunders' theory.

1. Introduction

Regards his original formulation of the Relative State theory (Everett 1957), Everett claims that, if analyzed in terms of his theory, «[f]ictitious paradoxes like that of Einstein, Podolsky and Rosen which are concerned with such correlated, non-interacting systems are easily investigated and clarified». Following the spirit of this claim, many of the Everett inspired theories boast to be local in nature, i.e., maintain to provide an account of quantum mechanics interactions in which all interactions are local. More often than not, however, important problems arise when such claims are investigated in greater detail. This is often the result of deeper troubles related to the resolution of fundamental problems within Everett's theory, first and foremost the interpretation of the concept of probability (Cfr. Barrett 1999). Since confusion in the matter is, to a large extent, due to problems dating back to the original theory, we think it would be appropriate to start this study with a quick review of the problems of probability and locality in Everett. The first section of this work will, thus, be dedicated to Everett's Relative State theory. In the remaining sections, we will face the problem of nonlocality, respectively, in Many Worlds, Many Minds and Simon Saunders' version of the Relational theory.

2. Relative State Theory

In the Relative State formulation of quantum mechanics, the Schrödinger equation is a complete description of the evolution of the world with no exception for the measurement processes. In the description of these, instead of considering only the evolution of the measured system as an open system, Everett's theory considers the composed system: observed system + measurement apparatus + observer. Let's say that the observer O is going to perform a measure of the observable B on the system S in the superposition state:

$$|S\rangle = \alpha|\varphi_B\rangle + \beta|\phi_B\rangle \quad (1)$$

where $|\varphi_B\rangle$ and $|\phi_B\rangle$ are eigenstates of B. At time τ, before the measurement is performed, the state of the composite system (Observer + Measurement apparatus + S) is:

$$|O + M + S\rangle^0 = |ready\rangle_O |ready\rangle_M (\alpha|\varphi_B\rangle_S + \beta|\phi_B\rangle_S) \quad (2)$$

According to the Schrödinger's equation, at time τ_1 after the measurement, the composite system should be in the state:

$$|O + M + S\rangle^1 = \alpha|\varphi_B\rangle_O |\varphi_B\rangle_M |\varphi_B\rangle_S + \beta|\phi_B\rangle_O |\phi_B\rangle_M |\phi_B\rangle_S \quad (3)$$

where the measurement apparatus and the observer are entangled with the observed system. In (3) the observer has not obtained a determinate result, and she's not in a definite state of registering it, but, as Everett put it, *relatively* to the state $|\varphi_B\rangle_S$ of the system, she is in the state of registering the corresponding eigenvalue, and equally for the state $|\phi_B\rangle_B$. Each component of the wave function is called here a *branch*, and the *branching* is responsible for our determinate experiences: these are the consequences of the fact that there is no interaction between branches, but "every subsystem" can only interact with the other subsystems' states that are in the same branch.

One of the most pressing problems in Everett's account is how to reproduce and interpret in a consistent way the quantum mechanical probabilities. In fact, on the one hand, once the process of the wave-function collapse disappears, Everett's theory lacks the necessary bridge between the deterministic evolution of the wave-function and the inherently probabilistic nature of quantum phenomena. On the other hand, if we eliminate Born's rule, we need another way of deriving quantum probabilities from the theory. In other words, in order to preserve self-consistency of the theory, Everett must prove that «the statistical assertions of the usual interpretation do not have the status of independent hypotheses, but are deducible [...] from the pure wave mechanics that start completely free of statistical postulates» (Everett 1957).

To begin with, Everett shows that in his model «a typical element [...] of the final superposition describes a state of affairs wherein the observer has perceived an apparently random sequence of definite results for the observation» (*Ibid.*) – and then he attempts to prove that such a sequence quantitatively respects the relative frequencies of quantum mechanics. In order to do that, he first provides a definition of probability which mimics the classical one: as in classical mechanics *probability* is defined as a measure over the phase space, similarly in quantum mechanics it is a measure over the states whose final superposition form the state vector. He then proceeds to show that only the density matrix is able to meet the requirements of countable additivity and normalisation. He then has to identify such a measure with the probability itself and, to this purpose, he claims that, over an infinite number of observations, almost all of the sequences of results (i.e., the results registered by observers in almost all of the branches) will ultimately reproduce the statistical results of quantum mechanics. To Everett, this is sufficient to claim that according to his theory a typical observer of the superposition should experience the right statistical frequencies results of quantum mechanics.

This conclusion is, however, not at all satisfactory. It is true that as the number of performed measurement goes to infinity, the sum of the component states where the frequencies of the results are different from those prescribed by quantum mechanics converges to 0. Anyway, the measurements performed are never infinite, so in general single component states do not show the right frequencies. Moreover, given that every possible result certainly actualizes after the measurement, it remains problematic to understand what probability means: the probability for each result, in one sense, is always 1. On the other hand, if we want to define probabilities relative to the results registered in one single branch, in order to make sense about future probabilities we have to give an account of the transtemporal identity of observers. In other words, in order to talk about the probability that Alice will register a determinate result after a measurement, we have first to decide *which* is the future Alice between those that will exist after the measurement.

Let's now approach the locality problem. In his 1973 paper, concerned with an EPR experiment on two singlet state particles Everett states: «One observer's observation upon one system of a correlated but non-interacting pair of systems, has no effect on the remote system, in the sense that the outcome or expected outcome of any experiments by another observer on the remote system are not affected» (Everett 1973).

Although he did not provide any further directions in order to explain this claim, a clarification of what he meant can be extracted by simply applying his model to the specific case study. Consider then an EPR-Bohm experiment: let *c* and *m* be two spin-1/2 particles, entangled in the spin singlet state:

$$|S\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_c|\downarrow\rangle_m - |\downarrow\rangle_c|\uparrow\rangle_m\right) \tag{4}$$

and let Alice and Bob be two observers, measuring each the spin along the *n* direction of particles *c* and *m*, respectively. At time τ, before any measurement is made, the status of the composite system Alice+Bob+c+m, can be written as:

$$|S + A + B\rangle^0 = |ready\rangle_A|ready\rangle_B \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_c|\downarrow\rangle_m - |\downarrow\rangle_c|\uparrow\rangle_m\right) \tag{5}$$

At time τ_1, after Alice has performed her observation, the system is in the state:

$$|S + A + B\rangle^1 = |ready\rangle_B \frac{1}{\sqrt{2}}\left(|\uparrow_n\rangle_A|\uparrow_n\rangle_c|\downarrow_n\rangle_m - |\downarrow_n\rangle_A|\downarrow_n\rangle_c|\uparrow_n\rangle_m\right), \tag{6}$$

according to which Alice has not recorded any definite result and the state of both particles remains unaltered: her measurement has not affected Bob's state nor the state of either of the two particles.

At time τ_2 when Bob performs his measurement on *m* the composite state becomes:

$$\left|S+A+B\right\rangle^{2}=\frac{1}{\sqrt{2}}\left(\left|\uparrow_{n}\right\rangle_{A}\left|\downarrow_{n}\right\rangle_{B}\left|\uparrow_{n}\right\rangle_{c}\left|\downarrow_{n}\right\rangle_{m}-\left|\downarrow_{n}\right\rangle_{A}\left|\uparrow_{n}\right\rangle_{B}\left|\downarrow_{n}\right\rangle_{c}\left|\uparrow_{n}\right\rangle_{m}\right) \quad (7)$$

Let us now assume that Alice and Bob proceed to verify the correlation between each other's measurements: since, according to Everett, there may not be any influence among branches of a superposition, every Alice only becomes conscious of the particular Bob who has registered a result completely anti-correlated to her own. The same result would apply if Alice and Bob should decide to perform two different measurements, say, *n* and *n'*, the only difference being the shape of the final state vector (at time τ_2):

$$\begin{aligned}\left|S+A+B\right\rangle''' = {} & \alpha\left|\uparrow_{n}\right\rangle_{A}\left|\uparrow_{n'}\right\rangle_{B}\left|\uparrow_{n}\right\rangle_{c}\left|\uparrow_{n'}\right\rangle_{m}+\beta\left|\uparrow_{n}\right\rangle_{A}\left|\downarrow_{n'}\right\rangle_{B}\left|\uparrow_{n}\right\rangle_{c}\left|\downarrow_{n'}\right\rangle_{m}+\\ & +\gamma\left|\downarrow_{n}\right\rangle_{A}\left|\downarrow_{n'}\right\rangle_{B}\left|\downarrow_{n}\right\rangle_{c}\left|\downarrow_{n'}\right\rangle_{m}+\delta\left|\downarrow_{n}\right\rangle_{A}\left|\uparrow_{n'}\right\rangle_{B}\left|\downarrow_{n}\right\rangle_{c}\left|\uparrow_{n'}\right\rangle_{m}\end{aligned} \quad (8)$$

We can assert that the reasons behind Everett's statements are a consequence of these assumptions:

1. In the relative state theory, not one, but all of the possible outcomes of a measurement exist after the experiment is performed.
2. There is a «total lack of effect of one branch on another» as branches evolves[1] (Everett 1973).

The disappearance of the wave-function collapse allows Everett to move around the "spreader" of the non-locality issue in standard quantum mechanics. Here, in fact, the correlation between results is justified by the collapse dynamics of the composite system, and nonlocality can emerge both within a spatiotemporal description of the collapse, and within an analysis of the behaviour of probabilities (which in standard quantum mechanics does not factorize) as in Bell's theorem. In Everett's theory, however, Alice (Bob) seems to evolve independently to Bob (Alice): she (he) interacts with the particle A (B), gets entangled with it, and (according to Everett's interpretation) registers all possible results – the correlation between the results obtained is then guaranteed by the fact that a determinate Alice (Bob) state can interact only with Bob's (Alice) state relative to it. However, removing the wave-function collapse is, alone, not a sufficient condition to guarantee locality of Everett's theory. In fact, we are going to see how the fulfilment of this will depend, first of all, on the detailed description of the branching process (there is always the possibility for it to be a nonlocal process), secondly, on the success of reproducing the right quantum probability, third, on providing an interpretation of probability. As we have seen, however, Everett does not provide any description of the branching process and his account of probability is wanting. This constitutes a problem for one who wishes to carry out a meaningful analysis in this sense.

In particular, given the nature of Everett's theory, the specific interpretation of the concept of probability is pivotal to the question whether Bell's inequalities are significant (i.e. of seeing if probabilities factorize) in each particular variant of the theory . As this crucial aspect has been recently stressed by Meir Hemmo and Itamar Pitowsky, a large part of this article will be dedicated to the consequences that their argument has for Many Worlds and Many Minds theories.

3. Many worlds

In the Splitting Worlds View (SWV) every measurement corresponds to a splitting of the "original" world into as many other real (material) worlds as the possible results of the measurement are. Every measurement, therefore, produce a multiplication of the real existing worlds, the observer included, who will end in a world where only one of the possible results is actualized. With this interpretation of the branches, DeWitt and Graham inherit the problem of interpretation of probability from Everett and face it with the same argument, which we have already concluded to be inconclusive. As we shall see later, the persistence of this shortcoming complicates the treatment of the local character of the theory in terms of Bell's inequalities. Nevertheless, the completely physical character of branches and of splitting allows us to approach the problem through a spatiotemporal description of the process. In the SWV, in fact, the splitting is described as an instantaneous process, i.e., the entire universe splits in all its points at the very moment in which the measurement takes place. To be sure, in Minkowski's spatiotemporal representation, the set of splitting events would have to be represented by a simultaneity hyperplane, but this means that the process of splitting would not be Lorenz-invariant, let alone local[2].

The Many Worlds interpretation developed by David Deutsch is in a sense a resolution of the two problems just seen in the SWV. In Deutsch's theory every element of the universal wave function corresponds to an infinity of worlds; when a measurement takes place the infinite set of worlds separates to form different (infinite) sets of worlds, each one corresponding to a possible result. The problem with Lorenz invariance is here avoided since there is in fact no splitting of worlds, but only a definitive separation (i.e. ending of interference) between worlds with different outcomes. The interpretation of probability finds here a clear and simple resolution: probability is a measure on the sets of worlds that separate after measurement, and is interpreted simply as the relative frequency of a result in the original undivided set of worlds.

In Rubin 2001, Mark Rubin asserts that the Many Worlds theory avoids the consequences of Bell's theorem since the counterfactual reasoning involved in Bell's theorem is not applicable to Many Worlds. Let's take an EPR experiment: depending on the kind of measurement performed on one side of the experiment, the set of worlds will divide into certain subsets within which certain particular properties will end up being determined. At the moment of the second measurement, hence, the properties of the world in which this will be performed (and so its initial conditions), will depend on the first measurement. On the other hand, Bell's theorem involves a counterfactual reasoning, which uses the assumption of equal initial conditions on one side regardless of what happened on the other side – hence, following Rubin, Bell's argument cannot be applied to Many Worlds theories.

Hemmo and Pitowsky (Hemmo and Pitowsky 2003), however, argue for the contrary and maintain that Deutsch's interpretation of probability legitimates the application of Bell's argument and, as a consequence, leads his theory to a strong form of nonlocality. Hemmo and Pitowsky's argument goes as follows. In the Many Worlds interpretation the evolution of the world is totally determined by the wave function. This means that the evolution is completely deterministic and, so, that the probabilities for the results of every possible measurement exist as a fact already before the measurements are fixed.

To be sure, in Deutsch's theory this means that already before the measurement and for every possible measurement it is decided what result will obtain in each singular world. But, Hemmo and Pitowsky's argument continues, «there is no (non-contextual) classical probability distribution which assigns the correct probabilities to all the branches of all possible trees simultaneously», and the only way in which we can fix probabilities in advance is by violating Bell's inequalities. This, in turn, implies a non-local influence of one side of the experiment on the other. In their article Hemmo and Pitowsky put Lockwood's Many Minds theory (see Lockwood 1996a and 1996b), which we will consider in a while, Saunders' 1998 formulation of his relational theory and Everett's 1957 formulation of the Relative State theory, in the class of theories to which this argument applies.

We find these last inclusions problematic. Regarding Everett's theory the problem lies in the difficulty of applying an analysis like the one just seen to a theory in which the interpretation of probability and the process of branching are so ambiguous. In our opinion two points are concerned in the problem. First, as we have already suggested we cannot understand what purpose a study of Bell's inequalities could serve, if performed within a theory which is not capable to produce quantum mechanical probabilities and in which, anyway, the very meaning of probabilities is deficient. Second, at the same way a spatiotemporal analysis of branching processes like the one provided for the SWI seems to be nonsense, given that in Everett's formulation it is not even comprehensible what kind of physical reality we can confer to branches.

The investigation of the case of Saunders' theory will be left for the last section.

3. Many Minds

The structure of Albert and Loewer's theory (Albert and Loewer 1988, Albert 1992) is deduced from two basic postulates:

1. The universal wave function provides a complete physical description of reality.
2. Through introspection we are able to obtain reliable data regarding our beliefs. Since introspection suggests that we always have well-defined beliefs, we induce that these cannot enter a superposition state.

Since, according to postulate 1, the physical components of an observer must generally be in a superposed state, and postulate 2 assures us that our beliefs are never in a superposed state, it also follows that beliefs obey a dynamics that is different from that obeyed by physical reality.

In the Many Minds Theory (MMT) of Albert and Loewer, every state representing an observer is tied to an infinite and continuous set of minds, non-physical entities whose evolution is genuinely random, not determined by the wave function, other than for the probability that each mind has to jump to a specific state after a measurement. The latter is provided by Born's rule. The separation between the evolution of a mind and that of the wave function is summarised in the assertion that *individual minds do not completely supervene onto the observer's physical state*.

Following Hemmo and Pitowsky, one can see how the assumptions of incomplete supervenience of minds on the physical world, together with the ensuing probability interpretation, allow Albert and Loewer's theory to avoid a strongly nonlocal character. Hemmo and Pitowsky affirm that their argument, as we have seen it in the case of Many Worlds, is applicable to Lockwood's MMT. This is because the former moves away from Albert and Loewer's MMT precisely in that (*i*) it assumes a complete supervenience of minds on physical states and that (ii) in it «[t]he standard Born rule defines a unique probability measure over subsets of minds, such that for any measurement (involving a conscious observer) the measure prescribes the proportions of minds following each final branch of the superposition.» (Hemmo and Pitowsky 2003, p. 9)

The concept of supervenience is pivotal to the application of Hemmo and Pitowsky's argument, so it is worth spending a few words on it. In Albert and Loewer's MMT, failure of supervenience is a consequence of the interpretation of probability: because the latter is interpreted as a classical probability of a mind seeing a determinate result *as a result of a stochastic process*, this means that the physical state does not totally rule the evolution of each single mind, but only of the proportion of minds. An expression of this is the fact that in Albert and Loewer's theory the physical state of an observer is not a complete description of her state and beliefs – to provide this, instead, a specification of partitions of sets of minds is needed. Let's say that an observer O measures the spin in direction *n* of a particle S in superposition state:

$$|S\rangle = \beta|\uparrow_n\rangle_S + \delta|\downarrow_n\rangle_S \tag{9}$$

and let's indicate with $|\uparrow\downarrow_n (m)\rangle\rangle_O$ a brain state of O followed by the subset *m* of minds. In Albert and Loewer's theory the state of the composite system S + observer after the measurement will be expressed by the following equation:

$$|S+O\rangle = \beta|\uparrow_n\rangle_S|\uparrow_n (m)\rangle\rangle_O + \delta|\downarrow_n\rangle_S|\downarrow_n (n)\rangle\rangle_O \tag{10}$$

while in Lockwood's theory the only specification of the brain state is a complete description of the set of minds partition[3]. Another way of explaining non-supervenience in Albert and Loewer's many minds is by saying that even if there exists some mind corresponding to the ↑ (say) component of O's physical state, not necessarily these will report a ↑ result.

Hence, in practice, in Lockwood's theory it happens that by assumption (*i*) we can bring the correlation results from the physical level to the mental one and by (*ii*) we can talk of a distribution of probability for each measurement and, consequently, apply Bell's theorem. On the other hand, in Albert and Loewer's theory minds evolve stochastically, the partition of the set of minds is only decided at the time of observation and the probability of each mind to follow one branch or the other is essentially determined by the *local* reduced state of the observer (there is no matter of fact about correlations between observers' minds), so that Bell's argument is not applicable. However, Hemmo and Pitowsky believe that, as a logical consequence of the way Albert and Loewer dealt with the *mindless hulks* problem, their MMT also implies a *weak* form of non-locality. The mindless hulks problem concerns the older Albert and Loewer's Single Mind theory and consists in the fact that, if to each observer corresponds only one mind and if its evolution depends from the reduced state of its owner alone, in an experiment such as, for instance, EPR, the probability that Bob's and Alice's minds will be really anticorrelated would be only one half. In the other half of the cases, in fact, both minds will actually interact with the anticorrelated component of the other, but this component will be in effect a mindless hulk. The only way to assure that both minds will end in the same branch is a non-local correlation between the two.

The problem of mindless hulks is not lack of empirical adequacy of the theory: quantum mechanical predictions of our experiences would be confirmed even without any correlation between minds' beliefs; still, this lack of consciousness of our interlocutors predicted by a *local* single mind theory has led Albert and Lower to abandon it in favour of the many minds theory. Now, let us return to Alice and Bob's experiment. In MMT there is no factual correlation between Alice's and Bob's minds, and yet, according to Albert and Loewer, the theory is consistent because the correlation between Alice's minds and Bob's report-state (and the other way around) is a sufficient condition for explaining quantum mechanical predictions. But in this regard Hemmo and Pitowsky find that there is a pretty strange implication of Albert and Loewer's theory, since it allows the possibility that, despite the fact that the set of Alice's (or Bob's) minds in state $\left|\uparrow\right\rangle_A$ sees a Bob (Alice) who claim to have recorded spin-down, the correlated minds of Bob (Alice) may in reality be in the state "registered spin-up" (failure of supervenience). But if we assume, as with the mindless hulks, that the absence of a mind behind our interlocutor creates a problem, so should the fact that the mind behind our interlocutor believes that she's saying the opposite of what we think she's saying.

So, Hemmo and Pitowsky conclude, we are forced to reject both possibilities: we must somehow correlate the observer's minds just like their physical states. Note, however, that this correlation does not, unlike in Lockwood's theory, violate the Bell inequality, which «requires the existence of a single probability measure defined over all possible (actual and counterfactual) measurements» (Hemmo and Pitowsky 2003, p. 16).

4. Saunders' Relational Theory

The relational interpretations consider quantum mechanics as treating interactions between systems, as opposed to systems themselves, and assume that this is the only possible way to describe physical reality (cfr. Laudisa and Rovelli 2002). In this same light Saunders' relational theory (see Saunders 1995, 1996, 1998, 2000) approaches relative state theory, employing in particular an interpretation of the branches introduced by the decoherent histories theory (cfr. Butterfield 2001).

In their above cited article Hemmo and Pitowsky affirm that the analysis they have conducted on Lockwood's theory is applicable *mutatis mutandis* even to the Relational theory, particularly the one outlined in Saunders 1998. In this section we will argue against this statement.

Saunders plans to resume and develop the concept of probability within the Relative State theory and defines probability in terms of relations between events. Specifically, probability is a fundamental relation, which «applies to states of affairs qua future, in relation to the present» and in this regard «the transition probabilities, [are] relations in the Hilbert space norm between future events and the present. *Correspondingly, probabilities are conditional, they are de facto relations*» (Saunders 1998, mine italics).

Probability only arises through branching; since branching only happens in the presence of decoherent phenomena, probability is also defined in terms of decoherence.

Just as in Lockwood's Many Minds Theory, and in contrast to Albert and Lower, in Saunders' theory the structure of events is entirely governed by dynamics. Hemmo and Pitowsky's claim on Saunders theory derives precisely from this feature of the theory –

however, we believe the former may escape the fate of Lockwood's MMT. As observed by Hemmo and Pitowsky, in fact, Bell's inequalities are a consequence of the fact that there exists no classical and non-contextual probability distribution, which assigns to each possible result of each possible measurement the same probabilities that are determined by quantum mechanics. However: «If probability only makes sense in the context of decoherence, which only arises for certain dynamical variables and in certain situations, why suppose that probabilities can be defined for arbitrary resolutions of the identity, with a non-contextual additivity requirement built in from the beginning?» (Saunders 2000). Notice that, even if this quotation comes from a later article than the one addressed by Hemmo and Pitowsky, still, we see that the very same characterization of probabilities is present in the previous quotation extracted from the 1998 paper. If we reject from the outset the imposition of the non-contextual additivity requirement on probability, Hemmo and Pitowsky's argument does not apply.

Now, the problem still remains to see if the contextual character of probabilities involves non-locality in Saunders' theory. This conclusion is in general not necessary, and, on the basis of both the interpretation which Saunders provides of branching and of a spatiotemporal description of it present in a recent paper by Guido Bacciagaluppi (see Bacciagaluppi 2002), elaborated in the spirit of Saunders' theory, we believe this is not the case.

The interpretation of probability and of branching present in Saunders 1998 has been later developed in Saunders 2000, precisely in view of the problem of non-locality in quantum mechanics. Here the discrepancy between quantum mechanics and special relativity is introduced as a problem in the idea of indeterminateness: the concept of an essentially undetermined future clashes with special relativity because the latter denies any ontological distinction between past, present and future. Such lack of accord is even more striking in quantum mechanics since here, lack of determinateness is inextricably linked to the formalism of the theory itself.

In the relational theory the distinction between determined and undetermined, as well as past and present, is merely a matter of convention; Saunders considers the universal wave-function, like space-time, from a full relational attitude: «Just as one combines all moments of time into space-time - obtaining a relational account of what is past and what is future - one combines all possible tree-diagrams, obtaining a relational account of what is determinate and what is indeterminate» (Saunders 2000).

Furthermore, just as the choice of a specific frame of reference is necessary in the space-time representation but not ontologically significant, the choice of a particular basis set in the representation of the wave function does not contain any fundamental ontological information.

A single basis set does not express the universal wave function and the projection operators possess definite values only referring to privileged places or systems. A necessary condition is that said operators must be defined according to local criteria of decoherence. It follows from this that the chosen basis cannot in any event be considered universal, but rather local: the projection operators are therefore local in Saunders' theory, acting only locally on the universal wave function.

As we have already seen at the end of section 2, Saunders points out very clearly how locality is a requirement which has to be imposed at the level of each single branch, and not at the level of the universal wave function – hence, the effective collapse process, that is what we actually observe, must be covariant: «The process is to be defined at each space-time point, as an effective state reduction on a certain threedimensional surface in space-time» (Saunders 2000).

Such a surface cannot, however, be space-like, since this would negate covariance: rather, it will be the future light cone surface relative to each point.

A work which shows how one can, within Saunders' strategy, provide a local interpretation of quantum mechanics has been carried out by Bacciagaluppi (Bacciagaluppi 2002), who provides us with a description of a branching space-time structure which can be the *locus naturalis* for a branching process described within the decoherent histories theory. Here branches are identified with *decoherent histories*, i.e. time ordered sequences of projectors which have to be exhaustive and exclusive. Each event in Bacciagaluppi's description of space-time is thus identified as a projector in a decoherent history. Just like Saunders, Bacciagaluppi proposes to employ the axioms of algebraic quantum field theory in order to provide a strictly local character to processes. In algebraic quantum field theory, in its operational interpretation, such axioms impose locality requirements on all possible measurements; when applied to decoherent histories, they become limitations on decoherence interactions. Since, however, in the theory of decoherent histories each decoherence phenomenon corresponds to a world branch, then a branching of Minkowski space-time can be assigned to these events; the divergence surfaces are the future light cones of the decoherent event.

Back to Alice and Bob. In the case described by Equation (7) the space-time branches generated by measurement events follow the future light cones of the two events and create two identical histories. When the divergence surfaces cross there is no further space-time branching. On the other hand, Equation (8) represents a situation in which Alice's measurement creates a space-time branching where c and m possess a definite spin along n direction, while Bob's measurement generates a different branching, where c and m possess a defined spin along direction n'. When the surfaces cross, another branching takes place and the space-time will be divided into four histories. This means that Bob's measurement can, eventually, affect Alice's only locally. In fact, either Alice's splitting is a process that is entirely independent of Bob's measurement (first case) or Alice's history is split again only when her world line crosses the future light cone of his measurement (second case). Recall that in standard quantum theory the wave-function collapse cannot take place in the future light cone. Since only one of all possible measurement results is actually observed, Aspect's experiment (cfr. Maudlin 1994) tells us that perfect correlation of results could be only explained by invoking an instantaneous influence of a measurement on the other. However, in Everett's theory all possible results are actualised and correlation between results is guaranteed by the rules of interaction among branches.

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Notes

[1] The lack of effect of one branch of another is an assumption made by Everett. In reality, the accuracy of this assumption depends on the precise interpretation that we provide of branches. If, for instance, we assume the SWV (see the following section), interference between branches is ruled out. Everett's claim can be seen, thus, as a point in favour of those who want the SWV to be the more true interpretation of the Relative State Theory.

[2] DeWitt and Graham does not provide a specific space-time description of the splitting. However, given that they do not make mention of a splitting space-time (like the one we will see later within Bacciagaluppi's many worlds view), we think it is legitimate to consider the splitting as taking place in an "usual" (non-splitting) space-time.

[3] In Lockwood's theory each observer has only one Mind (or *multimind*), which is "a subsystem of (the) body". Given that the Mind can enter in a superposition state, the definiteness of experiences is explained by Lockwood by those that he calls "maximal experiences", and that he defines as "complete state(s) of consciousness". The same Lockwood, however, makes propose maximal experiences as the equivalent of minds in Albert and Loewer theory, and it is so to the latter that Hemmo and Pitowsky address when they talk about Lockwood's many minds.