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OUTCOME PREDICTIONS AND PROPERTY ATTRIBUTION: THE EPR ARGUMENT RECONSIDERED

GianCarlo Ghirardi
International Centre for Theoretical Physics, Trieste, Italy,
Department of Theoretical Physics, University of Trieste, Trieste, Italy
and
Interdisciplinary Laboratory of the ISAS, Trieste, Italy

and

Renata Grassi
Department of Theoretical Physics, University of Trieste, Italy.

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ABSTRACT

We reconsider the nonlocal aspects of quantum mechanics with special reference to the EPR–argument. We first confine our considerations to the correlations between the outcomes of measurements on spatially distant constituents, without worrying about the measurement problem. We pay particular attention to the relativistic aspects of the problem. Our first conclusion is that, when developed along the lines we follow, the EPR inference that quantum correlations and locality together imply incompleteness, is appropriate. We then investigate whether the other common conclusion from the EPR argument, i.e. that standard quantum theory implies a spooky action at a distance, is correct. We emphasize the crucial role played by the locality assumption and we discuss the use of couterfactuals in the "relativistic" reformulation of the EPR argument. We show that the above conclusion is false if understood as saying that standard quantum theory exhibits, at least with reference to possessed elements of physical reality, some sort of parameter dependence. Thus, in a sense, the coexistence of quantum mechanics with relativity is even more peaceful than commonly thought.

We then go through a similar analysis by taking explicitly into account the measurement process. We point out the difficulties which one meets when confronting reduction mechanisms with relativistic requirements. This leads us to recognise the necessity of reconsidering the criteria for attributing objective properties to individual physical systems. Our final conclusion is that, in principle, it is perfectly possible to build up theories leading to the objectification of macroscopic properties which do not imply any spooky action at a distance.

1. Introduction

Probably the most striking and puzzling general implication of the quantum character of natural phenomena - which has been put into clear evidence in the celebrated paper[1] by Einstein, Podolsky and Rosen and even more in the important papers[2] by Bell - is nonlocality. This means that if the quantum mechanical predictions about the outcomes of measurement processes are true, then, under appropriate circumstances, events occurring in a certain space-time region may depend on events occurring in a space-like separated region. As is well known, this does not imply the possibility of faster-than-light signalling[3] (thus prompting the peaceful coexistence of quantum mechanics and relativity) since the nonlocality implied by the formalism is[4] of the uncontrollable type[5].

In what follows we will be specifically interested in considering individual physical systems and processes and in examining nonlocality from the point of view of individual systems. To make our argument definite without attempting to be too general we will mainly refer to a standard EPR-Bohm[6] like situation. We assume that the complete specification of the state of an individual physical system is given by appropriate parameters λ (which may include the quantum mechanical state vector or even reduce to it alone). We denote[7] by

$$p_\lambda^{LR}(x,y;\mathbf{n},\mathbf{m}) \tag{1.1}$$

the joint probability, given λ, of getting the outcome x ($x=\pm1$) in a measurement of the spin component along **n** at the left (L) and y ($y=\pm1$) in a measurement of the spin component along **m** at the right (R) wing of the apparatus. We assume that the experimenter at L can make a free-will choice of the direction **n** and similarly for the experimenter at R and the direction **m**. Both experimenters can also choose not to perform the measurement.

Bell's locality assumption can be expressed as the factorizability condition:

$$\text{B-Loc: } p_\lambda^{LR}(x,y;\mathbf{n},\mathbf{m}) = p_\lambda^{L}(x;\mathbf{n},*) \bullet p_\lambda^{R}(y;*,\mathbf{m}), \tag{1.2}$$

where the symbol * appearing in the probabilities on the r.h.s. denotes that the corresponding measurement is not performed.

As is well known[8,9], assumption (1.2) is equivalent to the conjunction of the following two logically independent conditions:

a. Parameter independence

$$\text{P.I.: } p_\lambda^{L}(x;\mathbf{n},\mathbf{m}) = p_\lambda^{L}(x;\mathbf{n},*); \qquad p_\lambda^{R}(y;\mathbf{n},\mathbf{m}) = p_\lambda^{R}(y;*,\mathbf{m}), \tag{1.3}$$

b. Outcome independence:

$$\text{O.I.: } p_\lambda^{LR}(x,y;\mathbf{n},\mathbf{m}) = p_\lambda^{L}(x;\mathbf{n},\mathbf{m}) \bullet p_\lambda^{R}(y;\mathbf{n},\mathbf{m}), \tag{1.4}$$

expressing that the probability of getting an outcome at L (R) is independent from the setting chosen at R (L), and that the probability of an outcome in one wing does not depend on the outcome which is obtained

in the other wing, respectively. We mention that standard quantum mechanics meets the P.I. requirement while violating O.I.

The above discussion of the non-local features of the theory makes reference to the outcomes of macroscopic measurement processes. Nonlocality presents new interesting aspects when one enriches the analysis, as was done (appropriately, in our opinion) in the EPR paper, by adding a new desideratum, viz. that one should be allowed, at least under appropriate circumstances, to speak of properties (or of elements of physical reality) objectively possessed by individual microscopic physical systems. If one makes this desideratum, the burden of the EPR argument is that, in a sense, even standard quantum mechanics with the completeness assumption exhibits a form of parameter dependence concerning these elements of physical reality. Roughly speaking, one could state that in a situation like the one discussed above, one could freely decide, by simply switching on an apparatus, whether to create, instantaneously, a property of a system far away.

It is the main aim of this paper to critically investigate this point. For this purpose we will follow two different (though related) lines, which will be presented in Sections 2 and 3 of the paper. In the first one we want to avoid dealing with the quantum measurement problem and to be quite general. In particular we will assume that measurements have outcomes and we will take as true of the process only the strict correlations predicted by the theory for what concerns the outcomes of measurements of spin components along the same direction at the two wings of the apparatus. The problems arising from taking into account the reduction mechanism and the ensuing implications for its relativistic description will be discussed in Section 3.

To start with let us go through an historical and critical reconsideration of the EPR argument and of the debate about it.

2. Reconsidering the EPR Argument in a Relativistic Context.

2.1. Introductory Considerations.

The celebrated paper written in 1935 by Einstein, Podolsky and Rosen[1] has been the subject of so many interesting investigations that it would be a hopeless task even to simply list them. We will not discuss here any of the contributions to this theme; we will limit ourselves to stressing that most of the literature is concerned with two fundamental points of ref.1, i.e. the reality and locality requirements. As regards the reality criterion, we will focus our attention on the possibility of "predicting" measurement outcomes, which in the EPR analysis constitutes the logical prerequisite of the very possibility of property attribution to individual physical systems.

The problem of the attribution of objective properties to individual physical systems was, at the time of the EPR paper, the crucial problem about which a passionate debate was going on. It is useful to recall that, according to Bohr, it is not meaningful to regard, in general, an individual microscopic quantum system as having any intrinsic property independent of some measuring instrument. In general, according to the Copenhagen interpretation there are no pre-existing values of physical observables of microscopic systems; it is the very act of measurement that produces them, rather than ascertaining their values. Said differently, the referent of the theory is what do we find not what is. The universe of discourse, the set of propositions the theory deals with, are conditional statements of the kind: "if such and such a measurement is performed [let us say a measurement of the observable $\mathcal{A}$], there is a probability p(a) of getting the outcome a".

One is naturally led to raise the question of the legitimacy of enlarging the universe of discourse (at least under appropriate circumstances) so as to include propositions of the type: "the individual system S has the property $\mathcal{A}$=a".

The EPR paper is fundamentally based on the desideratum that statements like the one above must be, at least in some cases, perfectly legitimate. Such cases are identified by resorting to the following minimal requirement: if, without in any way disturbing a system we can **predict** with **certainty** (i.e., with a probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.

This criterion allows one to exhibit, following the treatment of ref.10, a very general and simple derivation of the EPR paradox. With reference to the EPR-Bohm singlet state set-up considered in Section 1, we assume that the measurement at L and R both refer to the z-spin components of the two particles; (accordingly we will drop the subscript z

from the spin observables we will deal with). So measuring σ_R enables one to predict that a subsequent measurement of σ_L will show the opposite value to the one obtained for σ_R. Denoting by t_R the time of the measurement at R, we can infer, according to the EPR criterion, that the particle at L possesses an element of physical reality corresponding to σ_L for any time $t_L>t_R$. Adopting Einstein's locality requirement, in particular that a system's elements of physical reality cannot be changed by actions taking place at a distance, one can infer that the particle at L possessed this element of physical reality also for times $t_L<t_R$. But for such times the system is in the singlet state which does not contain any formal counterpart of this element of physical reality. So one concludes that quantum mechanics is incomplete.

We stress that the above analysis is performed within a non-relativistic context, i.e., assuming an absolute time ordering between events. So, an observer performing a measurement at (R,t_R) and finding a certain outcome, can predict the outcome of a subsequent measurement by another observer. The existence of an absolute time ordering is essential to guarantee a definite and unambiguous meaning to the word predict, which refers basically to possible future events. If one looks at the EPR-Bohm experiment from a relativistic point of view, one must take into account that since (L,t_L) and (R,t_R) are space-like separated there is no objectively defined time ordering between them. For this reason the observer at R cannot use his knowledge of the outcome of the measurement of σ_R at (R,t_R) to predict the outcome of a measurement in a space-like separated region. Consequently, the EPR criterion for property attribution is not satisfactory within a relativistic context, and it requires a detailed critical reconsideration.

2.2. A Short Digression: Counterfactuals.

In the next subsection, this reconsideration of the EPR criterion will lead us to deal with counterfactual statements. Thus, it seems appropriate to illustrate briefly that form of common-sense non-monotonic inference which is referred to as counterfactual reasoning which is of some use in clarifying the blurred notions of our everyday - and in some cases our scientific - use of "If ... then ..." statements. This holds in particular with reference to the analysis we want to perform.

A counterfactual is a statement of the "If ... then ... " type in which the antecedent is known (or expected) to be false. In our discussion it it will always be false. As a consequence, on the naive formalization using $\supset$ for "if ... then ..." all counterfactual statements would be true, contrary to our intuitive understanding of them.

A widely accepted way of dealing with counterfactuals is the one discussed in the lucid text[11] by D. Lewis, who treats them as variably strict conditionals in the usual possible worlds semantic for modal logic. This requires to make precise[12] how the truth-value at a given possible world of a counterfactual depends on the truth values at various possible worlds of its antecedent and consequent.

Let us denote the counterfactual "If ϕ were true, then ψ would be true" as "$\phi \Box\!\!\rightarrow \psi$" for propositions ϕ and ψ. Then Lewis proposes the following truth condition: $\phi \Box\!\!\rightarrow \psi$ is true at world w iff either (i) there are no possible worlds in which ϕ is true or (ii) some world where both ϕ and ψ are true is more similar ("closer") to w than any world in which ϕ is true and ψ is false. Obviously one has to specify the possible worlds one is taking into account; this is done by assigning to each world w a set of worlds S_w called[11] the sphere of accessibility around w.

We agree with Lewis that the concept of similarity between worlds is to some extent vague, but in various cases, in particular in those we will consider in what follows, this vagueness can be advantageously resolved by appropriate natural assumptions.

2.3. Property Attribution and Counterfactuals.

To analyse in full detail the EPR criterion for the attribution of elements of physical reality to individual physical systems and to investigate how one should adapt it to a relativistic context, we discuss a very simple example.

Suppose we are dealing with a spin-1/2 particle of which we know that, at the initial time $t=t_0$, its state vector is not an eigenstate of σ_z. Assuming that the spin is a constant of the motion, let us consider the following situation:

i). At time t_1 a measurement of σ_z is performed and yields the outcome +1;

ii). At time $t_M > t_1$, an observer who knows that σ_z has been measured at t_1 repeats the measurement and, obviously, he finds again the outcome +1;

iii). Finally, at time t_2 another measurement of σ_z is performed (and its outcome is, once more, +1).

The observer performing the measurement at t_M and finding +1, can predict that in the subsequent measurement at time t_2 the outcome will be +1, and thus, according to the EPR criterion, he can attribute the corresponding property to the system just before t_2. According to his knowledge the same observer can retrodict that the outcome of the measurment at t_1 has been +1, but he cannot legitimately state that just before t_1 the system possesses an element of physical reality corresponding to $\sigma_z=+1$. In fact, if one assumes that the quantum description is complete then, one must recognize that, due to the initial conditions, one could have obtained the outcome -1 in the measurement. This last assertion is clearly a counterfactual statement (since it refers to an alternative world, not the actual one). This shows how naturally counterfactuals enter in the problem of attributing elements of physical reality to individual physical systems[13].

Counterfactuals enter in a very natural way also in connection with the interpretation of the physical laws of quantum mechanics. Indeed if one maintains that counterfactuals must be avoided, one must to take a position à la Bohr according to which any analysis of a quantum phenomenon must take into account the whole experimental set up. Moreover, one has to say that one can meaningfully speak of probabilities of outcomes of a certain observable, only if an instrument designed to measure it is actually in place (note that in taking such a position one must identify probabilities with limits of relative frequencies). According to the lucid analysis of B. d'Espagnat[14]:

> "as a rule, however the physical probability laws are not of this kind. In classical physics, and also in most of the usual formulations of quantum mechanics, when we say that the probability of such and such a value of an observable A is equal to some number p what we mean is that if an appropriate instrument were placed at an appropriate location and if the experiment were repeated a large number of times, the value in question, let us call it a, would be

obtained in a fraction of the cases (approximately) equal to p. And we consider such a statement to be meaningful even in the cases in which no instrument is actually set that way ...".

To understand better the implications of the above example let us take now into account the case in which only the measurement at t_M is performed and the outcome +1 is obtained. The observer can make the following counterfactual assertion: if a measurement of σ_z is performed at time t_2 then the outcome is +1. In fact, in the considered case, it is possible and appropriate to define the accessibility spheres in terms of matching up to a time shortly before the time of the counterfactual's antecedent - in our case t_2 - and preserving the laws of nature or at least spin being a constant of motion, an assumption which is usually referred to[11] as inevitability at time t. Thus, in all the accessible worlds the outcome of the measurement at t_M ($t_M<t_2$) is the same as in the actual world (i.e. +1) and then, in all accessible worlds in which the measurement at t_2 is performed, the outcome is +1. This proves the truth of the counterfactual assertion. Of course, according to the Lewis criterion for truth conditions, any counterfactual statement specifying an outcome of a spin-measurement at time t_1, is not true.

Thus, we are led to link, with d'Espagnat[14], the attribution at time t of the property corresponding to σ_z=+1 to the truth of the counterfactual assertion: if a measurement of σ_z were performed at time t, then the outcome would be +1. This criterion for the attribution of elements of physical reality to individual physical systems derives quite naturally from the EPR criterion; and it is equivalent to it in those cases, like the present one, in which there is a definite absolute time ordering among events. But it allows us to deal with situations in which the EPR criterion, based on the possibility of predicting the outcome of a measurement, cannot be used because a definite time ordering is lacking. Therefore we consider it fully appropriate to base the analysis of the EPR paradox in a relativistic context on this criterion for the attribution of elements of physical reality to individual systems.

It is convenient, in order to prepare the ground for further developments to give a concise formal expression of the above argument. To this purpose we introduce some notational shortcuts:

$\mathcal{M}_S^{\mathcal{A}}(t)$: A measurement of the observable $\mathcal{A}$ of the physical system S is performed at time t.

$\mathbf{O}_S^{\mathcal{A}=a}(t)$: The outcome of $\mathcal{M}_S^{\mathcal{A}}(t)$ is $\mathcal{A}$=a.

$\mathcal{P}_S^{\mathcal{A}=a}(t)$: The system S possesses, at time t, the objective property (or the element of physical reality) $\mathcal{A}$=a.

Definition of Property Attribution: We relate the possibility of attributing a specific objective property to an individual physical system to the validity of a counterfactual statement[15]:

$$\textbf{P.A.1}: [\mathcal{M}_S^{\mathcal{A}}(t) \Box\!\rightarrow \mathbf{O}_S^{\mathcal{A}=a}(t)] \supset \mathcal{P}_S^{\mathcal{A}=a}(t). \quad (2.3.1)$$

We would like to stress that the above criterion **P.A.1** for property attribution allows inferences from statements involving propositions which constitute the natural universe of discourse for quantum theory, to the enlarged propositional system which allows sentences referring to objective elements of reality.

More generally, we will assert that the system S possesses an element of physical reality referring to the observable $\mathcal{A}$, and we will write $\mathcal{P}_S^{\mathcal{A}}(t)$, in accordance with the following prescription. Let us denote by $\hat{A}$ the self-adjoint operator associated to the observable $\mathcal{A}$. The corresponding eigenvalue equation is

$$\hat{A}|a_k> = a_k|a_k>. \quad (2.3.2)$$

The spectrum of the operator $\hat{A}$, which, for simplicity, we assume to be purely discrete, will be denoted by Sp{$\hat{A}$}. We now put:

$$\textbf{P.A.2}: \mathcal{P}_S^{\mathcal{A}}(t) \equiv_{df} \bigvee_{a_k \in Sp\{\hat{A}\}} \mathcal{P}_S^{\mathcal{A}=a_k}(t). \quad (2.3.3)$$

Thus, the truth of $\mathcal{P}_S^{\mathcal{A}}(t)$ is equivalent to the fact that S possesses an element of physical reality pertaining to $\mathcal{A}$. Note that $[\mathcal{M}_S^{\mathcal{A}}(t) \Box\!\rightarrow \mathbf{O}_S^{\mathcal{A}=a}(t)]$ holding true is a sufficient but not a necessary condition for the truth of the statement $\mathcal{P}_S^{\mathcal{A}}(t)$. For example: within quantum mechanics, one could know that the state vector is an eigenstate of $\mathcal{A}$ without knowing to which eigenvalue it belongs; or one could be dealing with a classical theory in which one can always claim $\mathcal{P}_S^{\mathcal{A}}(t)$, even though one has no specific information about the system under consideration and about the outcomes of hypothetical measurements.

Before coming to a precise analysis of the EPR argument along the lines we have just presented, it seems appropriate to deepen the discussion by recalling some conceptually relevant points. The argument considers two spatio-temporally separated systems. As appropriately stressed by Howard[16], in considering with such a situation we should distinguish two conceptually different principles: separability and locality. The first requires that[17] "whatever we regard as existing (real) should somehow be localized in time and space"; the second requires that events or objective properties pertaining to a space-time region A cannot be influenced by events occurring in a space-like separated region B. Usually, in discussing EPR like situations one pays little attention to separability, which is in a sense tacitly assumed as a prerequisite of the locality principle. We follow an analogous line. In fact, our aim in this Section is simply to show that the completeness assumption about quantum theory does not imply that, in EPR-like situations, something real concerning the system at L (R) is being created[17] as a consequence of a measurement on the system at R (L), the act of measurement being space-like with respect to the distant system. Equivalently, we aim to show that a system cannot be[18] "steered or piloted into one or another type of state at the experimenter's mercy in spite of his having no access to it".

2.4. The EPR argument - the Galilean case.

In this subsection we will limit ourselves to repeating in more formal terms the argument of Section 2.1. As we remarked there, we will make no use of incompatible measurements on R; we will simply take into account 2 incompatible outcomes, viz. ±1, for σ_{zR}. Thus our approach, following the line of many interesting papers[10,19] will be simpler than the original EPR one. As revealed by Fine[20] and Howard[16] this simpler argument is closer to Einstein's intentions.

We argue within a Galilean context: implying, as already remarked, an absolute time order and no backward causation. We assume that both in the actual and in the accessible worlds a measurement is performed at R at time t_R, and we are interested in counterfactual statements concerning the outcome of a possible measurement performed at L at time $t_L > t_R$. Thus:

i. $\mathcal{M}_{SR}^{\sigma}(t_R)$: A measurement of the z-spin component is performed on the particle at R at time t_R.

ii. $\mathcal{M}_{SR}^{\sigma}(t_R) \supset \mathbf{O}_{SR}^{\sigma=+1}(t_R) \vee \mathbf{O}_{SR}^{\sigma=-1}(t_R)$: such a measurement has as its outcome one of the two possible eigenvalues of σ_z.

We express the various assumptions which are used by resorting to appropriately abbreviated notations:

iii. $\forall t \in (t',t'')[(L,t)\{Iso\}(R,t_R)]$: Particle L is isolated from particle R for an appropriate time interval (t',t'') including both the time t_R at which particle R is subjected to the measurement and the time t_L.

iv. L{100% Corr}R: It is a law of nature (to be preserved in the accessible worlds) that the outcomes of spin measurements at L and R are 100% correlated.

v. G-Loc: A system cannot be affected by actions on a system from which it is isolated. In particular, elements of physical reality of a system cannot be influenced by actions on systems from which it is isolated.

The argument is then straightforward. Let us express it formally:

1. $\mathbf{O}_{SR}^{\sigma=+1}(t_R) \vee \mathbf{O}_{SR}^{\sigma=-1}(t_R)$ (by ii)

2. $\mathbf{O}_{SR}^{\sigma=+1}(t_R) \supset [\mathcal{M}_{SL}^{\sigma}(t_L) \Box\!\!\rightarrow \mathbf{O}_{SL}^{\sigma=-1}(t_L)]$ (by iv)

and: $[\mathcal{M}_{SL}^{\sigma}(t_L) \Box\!\!\rightarrow \mathbf{O}_{SL}^{\sigma=-1}(t_L)] \supset \mathcal{P}_{SL}^{\sigma=-1}(t_L)$ (by PA.1)

3. $\mathbf{O}_{SR}^{\sigma=-1}(t_R) \supset [\mathcal{M}_{SL}^{\sigma}(t_L) \Box\!\!\rightarrow \mathbf{O}_{SL}^{\sigma=+1}(t_L)]$ (by iv)

and: $[\mathcal{M}_{SL}^{\sigma}(t_L) \Box\!\!\rightarrow \mathbf{O}_{SL}^{\sigma=+1}(t_L)] \supset \mathcal{P}_{SL}^{\sigma=+1}(t_L)$ (by P.A.1)

4. $\mathcal{P}_{SL}^{\sigma}(t_L)$ (by 2,3 and P.A.2)

5. $\mathcal{P}_{SL}^{\sigma}(t^{\#})$ for some appropriate $t' < t^{\#} < t_R$ (by v and spin constant of motion)

6. The state vector at $t^{\#}$ is the singlet state. (hypothesis)

7. Quantum Mechanics is incomplete. (see below).

Formally, one usually expresses the essence of the argument by writing:

$[(100\%\ Corr)\wedge G\text{-}Loc]\supset\neg Compl.$

In steps 2 and 3 one derives, by iv, the truth of a counterfactual statement concerning $\mathbf{o}_{SL}(t_L)$ from a premise concerning $\mathbf{o}_{SR}(t_R)$. This, as in the case of a single system discussed in Section 2.3, is perfectly legitimate since within a Galilean context there is an absolute time ordering.

2.5. The EPR argument - the Lorentz case with the locality assumption.

We can now present the reformulation of the EPR argument which is appropriate for a relativistic context. In the relativistic framework, when speaking of two events A and B, one has to take into account three possibilities about their time ordering: A is in the future of B; A is in the past of B; and A and B are space-like separated. The interesting case for the EPR argument is the one in which the space-time region where the measurement on particle R occurs is space-like with respect to the space-time region[21] one is interested in for particle L. One can now understand why, in such a case, it seems inappropriate to relate the criteria for the attribution of properties to future events. Our formulation of the conditions which make the attribution legitimate, lead to a clean analysis of the argument and to a more appropriate understanding of the essential role of the locality requirement.

Obviously, some of the previous assumptions must be adapted to the new context, but this raises no problems and the way to do it is quite natural. We have simply to replace assumptions iii and v by the following ones:

iii. $[(L,t_L)(Space\text{-}Like)(R,t_R)]$: The space-time regions (L,t_L) and (R,t_R) are space-like separated.

v. L-Loc: An event cannot be influenced by events in space-like separated regions. In particular, the outcome obtained in a measurement cannot be influenced by measurements performed in space-like separated regions; and analogously, possessed elements of physical reality referring to a system cannot be changed by actions taking place in space-like separated regions.

With these premises the argument can be developed. We must, however, remark that, in spite of the similarity with the previous case, there is now an essential difference in the use one makes of the locality assumption. In fact, in the present case, such an assumption must enter into play from the very beginning. In the counterfactual argument leading to the assertion that there is an element of physical reality at (L,t_L), the antecedent is $\mathcal{M}_{SL}{}^{\sigma}(t_L)$. Accordingly, when defining the sphere of accessible worlds, in our opinion, one can keep as true everything independent of the occurrence of the left measurement. In fact, even though, in accordance with the previous considerations there is a certain vagueness about the definition of the accessibility spheres, due to the locality assumption v, it is quite natural to consider the outcome of $\mathcal{M}_{SR}{}^{\sigma}(t_R)$ as independent of the occurrence of $\mathcal{M}_{SL}{}^{\sigma}(t_L)$. This means that in all accessible worlds the considered outcome at right is the same as the one of the actual world.

Once this is clarified one can trivially go on and repeat exactly the steps from 1 to 4 of the previous section, arriving at the conclusion $\mathcal{P}_{SL}{}^{\sigma}(t_L)$.

Since, by the locality condition v, the element of physical reality existing at (L,t_L) is independent of whether or not the measurement at (R,t_R) has been performed, it should exist even if such a measurement is not performed. But in such a case the system is described by the singlet state. So, once more, one can correctly conclude that quantum mechanics is incomplete.

2.6. Assuming Completeness and so accepting nonlocality: the relativistic case.

The argument of the previous Section has made clear the crucial role of the locality assumption in deriving the EPR conclusion within a relativistic context. The final formal statement of Section 1.4 can also be expressed as

$[(100\%\ Corr)\wedge Compl.]\supset\neg Loc.$

As a consequence, a critical investigation of the implications of accepting nonlocality becomes necessary. In particular, one has to face Einstein's own question[22] whether quantum theory, when completeness is assumed, would imply some form of spooky action at-a-distance, in spite of the fact that it does not allow faster than light signalling.

This necessity of reconsidering the matter can be easily understood. As we have seen in the previous sections, the very requirements that one should be allowed, at least under appropriate circumstances, to speak of properties objectively possessed by individual physical systems and that the theory is complete, leads to the conclusion that such properties, in the Galilean case, emerge instantaneously as a consequence of the measurement which is performed on a distant system. This seems to allow one to state that, in spite of the analysis we have presented in Section 1, even standard quantum mechanics with the completeness assumption exhibits some form of parameter dependence; precisely the one referring to the possible instantaneous emergence of elements of physical reality.

We consider it essential to stress firmly that, in the relativistic case, one cannot draw such a conclusion. In fact let us investigate whether one can repeat the previous argument about possessed properties when the locality assumption is released. And here comes the crucial point. The very first step of the analysis, i.e. the assumption that for all the accessible worlds the specific outcome at (R,t_R) is the same as the one, e.g. $\mathbf{o}_{SR}^{\sigma=+1}(t_R)$, which has occurred in the actual world, when the locality assumption is given up, cannot be maintained. In fact, accepting nonlocality amounts exactly to admitting[23] that the outcome at (R,t_R) might depend on the occurrence of $\mathcal{M}_{SL}^{\sigma}(t_L)$. If it were not so, then the quantum correlations would not imply a genuine violation of Bell's locality condition but would simply correspond to occasional coincidences of outcomes[24].

The above arguments can be made quite convincing by considering, as we do in the next section, the example of a nonlocal hidden variable theory which is perfectly acceptable and makes clear why one cannot keep $\mathbf{o}_{SR}^{\sigma=+1}(t_R)$ to hold within the accessibility sphere.

2.7. A clarifying example.

Suppose we consider, in a relativistic context, a deterministic nonlocal hidden variable theory with the following features. There exists a set Λ in the space of the hidden variables such that $\lambda \in \Lambda$ implies that, if only the right measurement is performed, then the outcome +1 is

obtained. The set Λ is, however, the union of two subsets $\Lambda = \Lambda^+ \cup \Lambda^-$ such that, when both measurement are performed there is a difference between Λ^+ and Λ^-, as follows. While $\lambda \in \Lambda^+$ implies that the outcomes +1 and -1 are obtained at R and at L, respectively, $\lambda \in \Lambda^-$ implies that the opposite outcomes -1 and +1 are obtained. Obviously in the context of the unavoidable parameter dependence of deterministic hidden variable theories, this situation is quite natural.

It is obvious that in the above example, when considering counterfactual statements, what one has to keep fixed is the value of the hidden variable at the actual world. So, if $\lambda \in \Lambda^-$, the fact that in the actual world the outcome +1 has been obtained in the measurement at R cannot be taken as holding also for the accessible worlds.

2.8. Consequences of accepting nonlocality.

The arguments of the previous sections have made clear that, when locality holds and {100% Corr} is taken into account, the counterfactual statement $\mathcal{M}_{SL}^{\sigma}(t_L)\Box\!\!\rightarrow \mathbf{o}_{SL}^{\sigma=-1}(t_L)$ is non-vacuously true. But, as discussed in Sections 2.6 and 2.7, this does not hold when nonlocality is accepted.

As a consequence, if one assumes only that quantum predictions about outcomes are correct, the fact that in the actual world, in which only the measurement at R takes place,

$\mathbf{o}_{SR}^{\sigma=+1}(t_R)$

holds true, does not justify, by itself, either the counterfactual statement

$[\mathcal{M}_{SL}^{\sigma}(t_L)\Box\!\!\rightarrow \mathbf{o}_{SR}^{\sigma=-1}(t_L)]$,

or its opposite, i.e., the statement

$[\mathcal{M}_{SL}^{\sigma}(t_L)\Box\!\!\rightarrow \mathbf{o}_{SR}^{\sigma=+1}(t_L)]$.

To conclude: when one allows for nonlocality, one cannot make property attribution for the particle at L on the basis of one's knowledge about the particle at R. This obviously does not mean that, when nonlocality is accepted, the system at (L,t_L) possesses no objective properties; it simply means that in such a case, an argument of the EPR-type does not lead to its having such properties. This being the situation, it is obviously also illegitimate to claim that in an EPR-Bohm like situation there is instantaneous creation of properties at-a-distance.

2.9. Enriching the previous argument.

Up to this point we have adopted a strictly counterfactual point of view, in order to focus on the subtle points of the EPR analysis and to call attention to the inappropriateness of drawing certain conclusions from it. As we have repeatedly stressed, this requires the consideration of an actual world and of the appropriate spheres of accessible worlds.

Now we want to point out that one could have followed also another logical path to perform essentially the same analysis[25]. Namely, one considers only an actual world in which both measurements are performed. Concerning the outcomes of the measurements one can raise the following question: does knowledge about the system and the theoretical framework allow one to establish whether a certain outcome is determined or due to chance? In this approach, one assumes that when the outcome is determined (and noncontextual) then the individual physical system has an objective property corresponding to the considered observable.

One can repeat almost all previous arguments along these new lines. We will not present all the details; we will limit ourselves to making some general comments. To start with one can consider the example of Section 2.3. It is obvious that in this case one can legitimately state that the outcome of the spin measurement at $t>t_M$ is determined. Similarly, one can go through the EPR argument in the Galilean case and reach the conclusion that the outcome at (L,t_L) is determined. Consequently, there is an element of physical reality referring to the spin component of the particle at L.

Let us now consider the relativistic case when the locality assumption is made. As is well known[27]:

$[\{100\% \text{ Corr}\} \wedge \text{Loc}] \supset$ Determinism.

In fact, let j denote one individual of a pure ensemble of correlated composite systems described within quantum mechanics by the singlet state. Bell's locality requirement (1.2) implies, for the specific situation we are dealing with:

$$p_j^{LR}(+1,+1;z,z) = p_j^{L}(+1;z) \bullet p_j^{R}(+1;z) = 0 \quad (2.9.1a)$$

$$p_j^{LR}(-1,-1;z,z) = p_j^{L}(-1;z) \bullet p_j^{R}(-1;z) = 0. \quad (2.9.1b)$$

It is easily verified that Eqs. (2.9.1) imply that the outcomes at (L,t_L) and at (R,t_R) are determined. Obviously, since the two events (R,t_R) and (L,t_L) are space-like separated, similar conclusions can be drawn for both of them. Thus we can state that also in a relativistic context, when the locality assumption is made, the outcome (e.g.) at (L,t_L) must be determined and consequently that there is an element of physical reality referring to the spin component of the particle at L.

In the relativistic case one cannot reach the same conclusions when nonlocality is accepted. In fact {100% Corr} does not imply, by itself, that the two outcomes at the two wings of the apparatus are determined. Note that we do not claim that (e.g.) the left outcome is due to chance (which would amount to denying the existence of an objective property); we simply point out that one cannot legitimately state that it is determined. As a consequence one cannot speak of possessed spin properties for the particle at L.

2.10. Concluding Remarks.

In this first part we have critically reconsidered the EPR argument. We have seen that the conclusions of the seminal EPR paper are perfectly appropriate and correct not only for the Galilean context but also, provided locality is assumed, within a relativistic context. On the other hand, we have shown that the conclusion that quantum mechanics implies spooky actions at-a-distance, i.e. effects of parameter dependence, is not justified. This fact is, in our opinion, of some interest. For it shows that, the <u>peaceful coexistence</u> of standard quantum mechanics with relativity holds to a higher degree than is implied by the well known fact that nonlocality, being of the uncontrollable type, does not allow faster than light signalling.

3. Taking into Account Reductions.

3.1. Introductory Considerations.

The conclusions of Section 2 have to be taken into account, also when one wants to enrich the analysis, as we are going to do now, by taking into account possible reduction mechanisms. As we shall show, the counterpart of the impossibility of attributing properties to individual systems is the emergence of ambiguities in the expectation values of local observables; and this fact prompts a reconsideration of the whole problem of the identification of the elements of physical reality.

To be allowed to speak of measurement outcomes, one has to account, in one way or another, for the emergence of definite properties of the physical systems that play the role of measuring apparata. Although the nature of measurement is of course very controversial, we believe that to account for such definite properties one has to consider explicitly the occurrence of statevector reduction either by postulating it or by deriving it from an appropriately modified dynamics. So, in this part we will reconsider the same problems discussed in Section 2, taking however into account the reduction process. We will discuss the difficulties one meets when trying to incorporate the wave packet reduction postulate within a relativistic framework. We will also analyse the implications of considering explicit models of dynamical reduction[28-30,26] which have been presented recently and which do not exhibit parameter dependence (barring some extremely improbable situations).

3.2. The Standard Theory with Wave Packet Reduction.

As we use the term, the "standard scheme" means simply the assumption that as a consequence of the system-apparatus interaction wave packet reduction takes place. On this assumption one can relate the properties of individual physical systems directly to the statevector. Let $\hat{A}$ be the self-adjoint operator associated to the observable $\mathcal{A}$ we are interested in, a one of its eigenvalues and P_a the projection operator on the corresponding eigenmanifold.

Definition of Property Attribution: We relate an individual physical system possessing an objective property to the validity of an appropriate relation[31] for the statevector describing the system at time t:

$$\mathcal{P}_S^{\mathcal{A}=a}(t) \equiv_{df} [\| P_a |\Psi, t> \| = 1]. \tag{3.2.1}$$

With reference to the usual EPR-Bohm set-up we can develop the analogue of the arguments of Sections 2.4 and 2.5 by making use of this criterion for property attribution. Only one macroscopic apparatus is present (e.g. at the right wing) measuring, at time t_R, the spin component along the z-axis. One is interested in z-spin properties of the particle at the left wing at a time t_L subsequent to t_R.

a. *Galilean Context*

Wave packet reduction (WPR) is assumed to take place instantaneously. We have as before:

i. $\mathcal{M}_{SR}^{\sigma}(t_R)$.

ii. $\mathcal{M}_{SR}^{\sigma}(t_R) \supset [\mathcal{O}_{SR}^{\sigma=+1}(t_R) \vee \mathcal{O}_{SR}^{\sigma=-1}(t_R)]$.

The formal argument is then straightforward:

1. $\mathcal{O}_{SR}^{\sigma=+1}(t_R) \vee \mathcal{O}_{SR}^{\sigma=-1}(t_R)$

2. $\mathcal{O}_{SR}^{\sigma=+1}(t_R) \supset \{(\forall \varepsilon > 0), |\Psi, t+\varepsilon> = |S_L, \sigma=-1> \otimes |S_R, \sigma=+1>\}$ (by WPR)

and: $\{(\forall \varepsilon > 0), |\Psi, t+\varepsilon> = |S_L, \sigma=-1> \otimes |S_R, \sigma=+1>\} \supset [\| P_{\sigma_L=-1} |\Psi, t+\varepsilon> \| = 1]$

and: $[\| P_{\sigma_L=-1} |\Psi, t+\varepsilon> \| = 1] \supset \mathcal{P}_{SL}^{\sigma=-1}(t_L)$ (by 3.2.1)

3. $\mathcal{O}_{SR}^{\sigma=-1}(t_R) \supset \{(\forall \varepsilon > 0), |\Psi, t+\varepsilon> = |S_L, \sigma=+1> \otimes |S_R, \sigma=-1>\}$ (by WPR)

and: $\{(\forall \varepsilon > 0), |\Psi, t+\varepsilon> = |S_L, \sigma=+1> \otimes |S_R, \sigma=-1>\} \supset [\| P_{\sigma_L=+1} |\Psi, t+\varepsilon> \| = 1]$

and: $[\| P_{\sigma_L=+1} |\Psi, t+\varepsilon> \| = 1] \supset \mathcal{P}_{SL}^{\sigma=+1}(t_L)$ (by 3.2.1)

4. $\mathcal{P}_{SL}^{\sigma}(t_L)$ (by 2,3 and P.A.2)

b. *Relativistic context*

An important difference from the previous case derives from the necessity to identify precisely the modalities of the reduction mechanism. Let us start by considering the observer O who performs the measurement at R and let us tentatively assume that wave packet reduction takes place instantaneously in his reference frame. For such a reference frame the same argument as before and the ensuing conclusions seem to follow legitimately.

However, in the present case, for arbitrarily large L-R space separations, even for an observer O' moving with extremely low velocity with respect to O, it may happen that $t'_L<t'_R$. If the theory must exhibit at least a ghost of Lorentz invariance, one has to assume that, even for O', WPR takes place instantaneously in his reference frame at the time t'_R at which the system-apparatus interaction occurs. This means that, in place of propositions 2 or 3 or 4 above (which holds true in the present case for the observer O) observer O' has:

4'. $[|\Psi',t'_L>=|Singlet>] \supset [||P_{\sigma'_L=-1}|\Psi',t'_L>||=||P_{\sigma'_L=+1}|\Psi',t'_L>||=\frac{1}{2}]$

and: $[||P_{\sigma'_L=-1}|\Psi',t'_L>||=||P_{\sigma'_L=+1}|\Psi',t'_L>||=\frac{1}{2}] \supset \neg \mathbf{P}_{SL}{}^{\sigma}(t'_L)$.

The situation is summarised in Fig. 1a and 1b. The conclusion should be obvious: if one accepts the postulate of WPR and tries to make the reduction mechanism covariant one has to face the following difficulty:

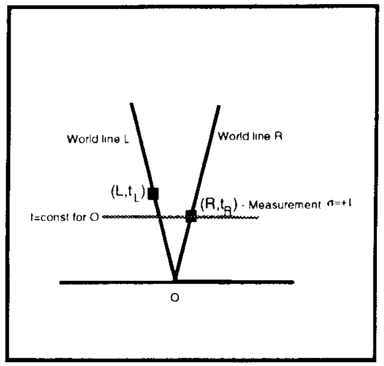

Fig.1a

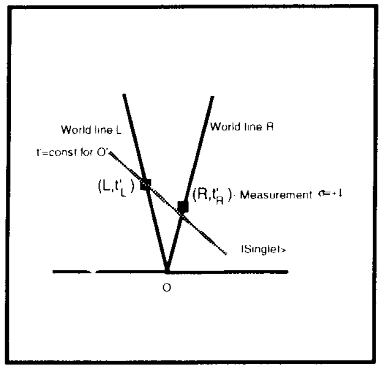

Fig.1b

Fig.1.- Instantaneous wave packet reduction for different observers.

observers O and O' cannot agree on a statement referring to a local property at a space-time point. This shows the inappropriateness of

claiming, without a more detailed analysis, that there is instantaneous creation of properties at-a-distance[33].

3.3. Relativistic Dynamical Reduction Models

In recent years various attempts have been made[28] to describe, at the nonrelativistic level, wave packet reduction on the basis of a unified dynamics governing all natural processes. Relativistic generalisations of such models have also been presented[26, 29, 30]. Even though they meet serious mathematical difficulties, more specifically the appearance of intractable divergences, these theoretical frameworks yield interesting new insights about the issues of this paper.

Within the model of refs. (26, 29, 30), the dynamical reduction mechanism is governed by a skew-hermitian coupling between appropriate field operators and c-number white noise processes. More precisely: one works in the Interaction Picture and assumes that the fields are solutions of the Heisenberg equations of motion obtained from a Lagrangian density $L_0(x)$. We remark that $L_0(x)$ is not assumed to describe only free fields. The statevector evolves according to the Tomonaga-Schwinger equation:

$$\frac{\delta|\Psi_V(\sigma)>}{\delta\sigma(x)} = [L_I(x)V(x) - \lambda L_I^2(x)]|\Psi_V(\sigma)> \qquad (3.3.1)$$

where $\sigma(x)$ is a space-like surface, $L_I(x)$ is the Interaction Lagrangian density in the Interaction Picture and $V(x)$ are c-number stochastic "potentials" satisfying:

$$<<V(x)>>=0; \quad <<V(x)V(x')>>=\lambda\delta(t-t')\delta(\mathbf{x}-\mathbf{x}') \qquad (3.3.2)$$

The evolution equation does not preserve the norm of the statevector but it preserves the average square norm. It has to be supplemented by the following prescriptions:

- Given the initial statevector on the space-like surface σ_0, the statevector on the arbitrary space-like surface σ lying entirely in the future of σ_0 is obtained, for a particular occurrence of the stochastic potential V, by solving the above equation (3.3.1) with the considered initial conditions and normalizing the resulting statevector.

- The actual probability of occurrence $P_C[V]$ of the stochastic potential V is determined by resorting to a "cooking procedure" of the "natural" probability P[V] of occurrence (i.e. the one associated to the white noise processes defined by (3.3.2)). The "cooking" involves the norm of the solution of Eq.(3.3.1) according to:

$$P_C[V] = P[V] \| |\Psi_V(\sigma)> \|^2. \qquad (3.3.3)$$

It is important to stress that Eq.(3.3.1) is integrable. The explicit case which has been most widely discussed is that of a fermion field coupled to a real scalar meson field by a standard trilinear coupling, so that the Lagrangian density $L_0(x)$ contains, besides the terms describing the free fields, an additional term

$$g\overline{\Psi}(x)\Psi(x)\Phi(x). \qquad (3.3.4)$$

g being a coupling constant. Moreover the choice

$$L_I(x) = \Phi(x) \qquad (3.3.5)$$

is made for the interaction term appearing in Eq.(3.3.1).

As discussed in full detail in refs. 29 and 30, this model assigns to each space-like hypersurface a unique, well defined state vector (so that no difficulties arise in connection with nonlocal observables); and the reduction occurs as soon as the hypersurface crosses, towards the future, the space-time region where a macroscopic measurement process takes place.

For our interests here, the most significant feature of the model is that, due to the skew-hermitian nature of the coupling in the Tomonaga-Schwinger equation, at the individual level (unlike the ensemble level) the expectation value of a local observable with compact support depends on which space-like hypersurface, among all those containing its support, is considered. This means that:

$$\frac{<\Psi(\sigma_1)|A_I|\Psi(\sigma_1)>}{<\Psi(\sigma_1)|\Psi(\sigma_1)>} \neq \frac{<\Psi(\sigma_2)|A_I|\Psi(\sigma_2)>}{<\Psi(\sigma_2)|\Psi(\sigma_2)>}$$

in spite of the fact that, since the support of A_I is space-like with respect to the space-time region where the measurement takes place, A_I itself commutes with the operator describing the evolution from σ_1 to σ_2.

3.4. Reconsidering the EPR Argument within the New Context.

We consider once more our EPR-Bohm like example and we denote by $P(L,\sigma=-1)$ the projection operator associated to the local observable "component along z" of the spin of the particle at (L,t_L). Since:

1. $[(L,t_L)$ {Space-Like} $(R,t_R)]$

there are both space-like surfaces through (L,t_L) which pass below (R,t_R) and surfaces which pass above it. Because dynamical reduction is induced by crossing the region containing the macroscopic apparatus, it follows that while the mean value of this local projection operator is extremely close to 1 on the surfaces passing above (R,t_R), it takes a value extremely close to 1/2 on those passing below it.

Thus this model exhibits the same kind of ambiguity we have met in Section 3.2. This should be expected. In fact, the dynamical reduction models and their generalisations are simply, as remarked by J. Bell [28]: quantum mechanics with WPR made rational.

3.5. The Criteria for Property Attribution Reconsidered.

The analysis of the previous sections prompt us to reconsider the criteria, modelled on the nonrelativistic case, that we have adopted for property attributions to individual physical systems. For this purpose we denote, in analogy with Section 2, by $\mathcal{A}$ a local observable with compact support, by a one of its eigenvalues and by P_a the associated projection operator.

Definition of Property Attribution for the Relativistic Context: We relate an individual physical system possessing an objective local property to the expectation value of the appropriate projection operator on the whole family of space-like surfaces containing its support:

$$\mathcal{P}_S^{\mathcal{A}=a} \equiv_{df} (\forall\sigma)\{[\sigma\text{-space-like} \wedge \text{support of } \mathcal{A} \in \sigma] \supset (\exists a)[\| P_a|\Psi(\sigma)> \| \equiv 1]\} \; . \qquad (3.5.1)$$

Some remarks:

- According to this criterion, together with the analysis of Section 3.4, the occurrence of $\mathcal{M}_R^{\sigma}(R,t_R)$ does not imply the creation of elements of physical reality for the particle at L until the space-time region in which its world-line crosses the future light cone originating from (R,t_R); see Fig. 2.

- The fact that a constituent of a microsystem can have no property at all is, of course, not peculiar to this criterion. In general, if the spin state of the composite system is entangled and no measurement at all occurs, neither of the constituents possesses objective properties for spin. So, the criterion simply requires this to hold true for a constituent, for an appropriate time interval, also when a measurement occurs on the other constituent.

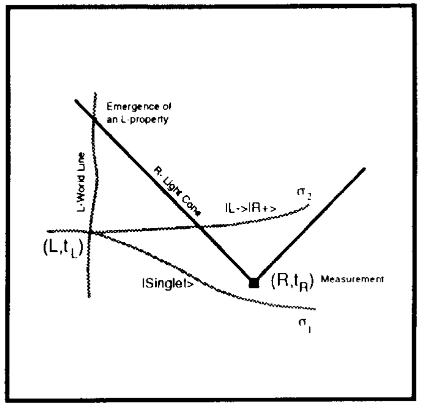

Fig.2.- Emergence of a property according to the relativistic criterion for the attribution of elements of physical reality of Section. 3.5.

- As we will show in Section 3.8, the situation is radically different when one considers an analogous process involving two macroscopic objects in space-like separated regions.

- Finally, this criterion also makes acceptable the covariant version of the WPR postulate described in Section 3.2. Obviously this does not make the dynamical reduction program useless. For the motivation for such a program does not stem just from the desire to deal with the relativistic aspects of the reduction process; but mainly from the desire to make WPR compatible with the unique dynamics which governs all phenomena

contrary to what happens for the standard theory, in which WPR plainly contradicts the linear nature of the evolution equation.

3.6. The Slight Parameter Dependence of Relativistic Dynamical Reduction Models.

Strictly speaking, and as has been discussed in detail in recent papers[34], even within the relativistic dynamical reduction model considered in Section 3.3, there are still (extremely improbable) nonlocal effects of the kind which make macroscopic outcomes parameter dependent; and also (extremely improbable) nonlocal EPR effects in which an objective property can be modified by a far away free-will choice. We will confine ourselves here to this last possibility.

Consider two particles which are emitted from a common origin in the normalized spin state

$$|\Psi\rangle = \alpha|L,\sigma=-1\rangle|R,\sigma=+1\rangle + \beta|L,\sigma=+1\rangle|R,\sigma=-1\rangle \quad (3.6.1)$$

where $|\alpha|^2$ is extremely close to 1. According to our criterion, the particle at L possesses the property σ^L=-1. Suppose now that at (R,t_R) there is an observer who can, at free will, switch on an apparatus devised to measure σ^R. According to the standard theory, as well as to the dynamical reduction models, there is an extremely small but nonvanishing probability $|\beta|^2$ that, if the apparatus at R is switched on, the outcome σ^R=-1 is obtained. Suppose this happens. Let us now describe the general picture.

At a point on the world line of the L-particle that lies outside the light cone from (R,t_R) there are both space-like surfaces which pass below (R,t_R) and space-like surfaces which pass above (R,t_R). The mean value of the projection operator associated to the value +1 for the z-spin component of the L-particle at such a point is, given that the measurement at (R,t_R) yields σ_R=-1, very close to zero for the earlier hypersurfaces and very close to one for the later hypersurfaces. Then, according to our criterion, the particle at L does not possess any property corresponding to this local observable; and this is just due to the fact that the measurement at R has been performed. One could then assert that such a measurement has influenced the physical property of a system in a space-like separated region.

The above conclusion is certainly correct and cannot be avoided since it is logically implied by the formal structure of the theory. However, we emphasize that these peculiar effects have such a low probability of occurrence that they can in practice be disregarded.

We shall also mention that one could also make other choices about the criteria for the attribution of properties related to local observables. One possibility is the following:

-Define $\Sigma(\mathcal{A},\sigma_0)$ to be the space-like surface that consists of the compact support of $\mathcal{A}$, the past light cone originating from it, and the part of the hypersurface on which the initial conditions are assigned that lies outside this past light cone. Then one adopts the following criterion for property attribution: a physical system S possesses the objective property $\mathcal{A}$=a when the mean value of $P_{:}$ is extremely close to 1 on $\Sigma(\mathcal{A},\sigma_0)$.

If this criterion is adopted, the theory would exhibit no nonlocal effects of parameter dependence, as well as no nonlocal effects of the type discussed above, not even with extreme improbability. The reason for this should be obvious. The statevector (and consequently the possessed properties) associated to $\Sigma(\mathcal{A},\sigma_0)$ is by no means influenced by the measurement process as long as the spatial support of $\mathcal{A}$ is space-like with respect to the space-time region in which the measurement occurs. Only when the past light cone from the support of $\mathcal{A}$ includes (R,t_R), i.e. only when a luminal propagation allows the measurement to influence the property of the left particle, can the properties of this particle depend on whether the measurement at (R,t_R) is performed or not.

To avoid being misunderstood, we should stress that the above considerations allow the theory to exhibit nonlocal effects at the individual level. Actually the relativistic dynamical reduction models exhibit outcome dependence just as standard quantum mechanics does[34]. This dependence finds its origin in the correlations between the two stochastic potentials which give rise to outcomes reproducing quantum predictions, when one has two apparatuses which are both switched on.

3.7. Micro-events versus Macro-events.

Thus, the conclusion of the this third section is that it is possible to build up theories that (i) account for reduction as a dynamical process in which no element of physical reality can be influenced by actions

performed at space-like points; and that (ii) do not exhibit parameter dependence (barring cases having extremely small probability of occurrence), and therefore do not entail any spooky action at a distance. To fully appreciate the precise meaning and the implications of these assertions, it turns out to be useful to deepen the analysis by comparing the case in which one measuring apparatus is present with the one in which two macroscopic apparata are present.

Let us consider, first of all, a possible objection to our analysis. One might be tempted to say: so what? You have played a trick, you have changed in an ad-hoc way the criteria for property attribution so that in all puzzling cases which one encounters you can claim that there is no element of physical reality. Our answer is that the above criterion is a fairly natural one and it solves the problem very neatly. Moreover, we would like to stress that, due to the reduction dynamics, the criterion has quite different implications in the cases of microscopic and of macroscopic systems. In particular, while one is led to admit that at the microscopic level an individual system can possess no property, i.e., in J. Bell's words[35] can enjoy the vagueness of waves, the situation is quite different for macroscopic systems. To show this in more detail, we will now give an analysis, similar to the preceding ones, but in which there are, in the actual world, two macroscopic apparata at L and R which are both switched on.

3.8. Performing two measurements.

With reference to Fig.3, we consider a situation in which two particles in the singlet state trigger two macroscopic apparata[36] in two space-like separated regions. In the figure the squares L_1 and R_1 denote the space-time regions where the interactions between the particles and the apparata (which trigger the recording process by the macroscopic apparata) take place; while the squares L_2 and R_2 denote the space-time regions where the stochastic processes leading to reduction, i.e. to the localisation of the macroscopic pointers, occur.

The initial state on the space-like surface σ_0 is (disregarding the configuration space part describing the propagation of the particles towards left and right):

$$|\Psi(\sigma_0)\rangle = \frac{1}{\sqrt{2}}[|L,\sigma=-1\rangle|R,\sigma=+1\rangle - |L,\sigma=+1\rangle|R,\sigma=-1\rangle]|\chi_{L0}\rangle|\chi_{R0}\rangle \quad (3.8.1)$$

where $|\chi_{L0}>$ and $|\chi_{R0}>$ describe the untriggered (ready) states of the apparata at left and at right, respectively.

Let us change the surface by going from σ_0 to σ_0^*. The right particle triggers the apparatus at right, so that:

$$|\Psi(\sigma_0^*)> = \frac{1}{\sqrt{2}}[|L,\sigma=-1>|R,\sigma=+1>|\chi_{R+}> - |L,\sigma=+1>|R,\sigma=-1>|\chi_{R-}>]|\chi_{L0}> \quad (3.8.2)$$

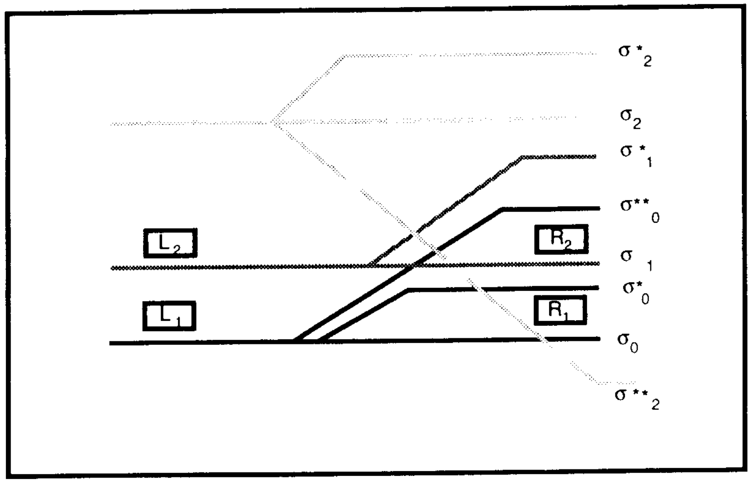

Fig.3.- Properties for entangled macroscopic systems.

If one changes once more the surface and goes to σ_0^{**}, i.e. one crosses the region where the stochastic reduction process occurs, then, assuming that the measurement at R yields the outcome +1, one gets the statevector:

$$|\Psi(\sigma_0^{**})> = [|L,\sigma=-1>|R,\sigma=+1>|\chi_{R+}>]|\chi_{L0}>. \quad (3.8.3)$$

We emphasize that on all these three space-like surfaces the statevector is factorized into the direct product of a state belonging to the Hilbert space of the left apparatus and the rest. Moreover the factor describing this apparatus is $|\chi_{L0}>$, so that the apparatus possesses, in the region lying "below L_1", the objective property of being in the ready state, i.e. its pointer "points at 0".

Let us now consider the situation on the space-like surface σ_1 on which both particles have triggered the appropriate apparata. We have:

$$|\Psi(\sigma_1)> = \frac{1}{\sqrt{2}}[|L,\sigma=-1>|R,\sigma=+1>|\chi_{R+}>|\chi_{L-}> - |L,\sigma=+1>|R,\sigma=-1>|\chi_{R-}>|\chi_{L+}>] \quad (3.8.4)$$

while, if one crosses the region where the reduction of the right apparatus states take place, i.e. if one reaches the space-like surface σ_1^*; one has:

$$|\Psi(\sigma_1^*)> = [|L,\sigma=-1>|R,\sigma=+1>|\chi_{R+}>|\chi_{L-}>]. \quad (3.8.5)$$

Comparison of the last two equations shows that there is an ambiguity about the property of the macroscopic measuring apparatus at left in the region "between L_1 and L_2".

However, let us now consider the space-like surface σ_2. On it the statevector turns out to be:

$$|\Psi(\sigma_2)> = [|L,\sigma=-1>|R,\sigma=+1>|\chi_{R+}>|\chi_{L-}>] \quad (3.8.6)$$

and this precise state has to be associated to all surfaces which pass above the region L_2, in particular to σ_2^* and even to a surface like σ_2^{**}. So, in accordance with our criterion for attributing properties, we can state that the apparatus at left possesses, in the region lying "above L_2", the objective property that its pointer "points at –".

3.9. Conclusions.

The detailed analysis of the previous subsection has shown that, even though ambiguities (and correspondingly the lack of definite properties) can occur also for macroscopic systems and outcomes, such ambiguities last only for the characteristic reduction times of the theory which, in these models, are extremely small.

Thus we could say, rephrasing a statement[35] by J. Bell that, just as nonrelativistic reduction models allow microsystems to enjoy the vagueness of waves, but require tables and chairs and pointers to possess objectively definite macroscopic properties (actually those of "being at definite places") independently of our free choice to acquire knowledge of such properties; so also the relativistic generalisations of such models show that a microsystem can still enjoy the vagueness which characterises the quantum world, even when it is entangled with another system and its partner is subjected to a measurement. In order that the microscopic system acquires objective properties, the time required for a luminal propagation from the region where its partner has been measured to its own region has to elapse. On the other hand, a macroscopic system can remain in the vague situation which characterises quantum superpositions only for "a split second", independently of any entangling mechanisms which may be operative and/or knowledge that some conscious observer might have about other macroscopic systems.

Obviously, the above statements would be fully appropriate only if a perfectly satisfactory relativistic reduction model were available. As we have mentioned above, such a program at present still faces some serious difficulties. But we take the third section of this paper to indicate that there are no logical or conceptual reasons that forbid a fully satisfactory development of the relativistic reduction program. We hope also to have identified some typical features that models of this type must exhibit.

Acknowledgments

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References and Footnotes.

1. A. Einstein, B. Podolsky and N. Rosen, 'Can Quantum Mechanical Description of Physical Reality be Considered Complete?', Physical Review, **47**, 777-780 (1935).

2. J. S. Bell, 'On the Einstein-Podolsky-Rosen Paradox', Physics, **1**, 195-200 (1964); 'Introduction to the Hidden Variable Question' in: Foundations of Quantum Mechanics, B. d' Espagnat ed., Academic, New York, 171-181, (1971).

3. P. Eberhard, 'Bell's Theorem and the Different Concepts of Locality', Nuovo Cimento, **46 B**, 392-419 (1978); G.C. Ghirardi, A. Rimini and T. Weber, 'A General Argument against Superluminal Transmission through the Quantum Mechanical Measurement Process', Lettere Nuovo Cimento, **27**, 293-298 (1980).

4. A. Shimony, 'Controllable and Uncontrollable Non-Locality', in: Proceedings of the International Symposium on the Foundations of Quantum Mechanics, S. Kamefuchi et al. eds., Physical Society of Japan, Tokyo, 225-230 (1983).

5. Having practical control of nonlocality would imply by itself the possibility of preparing ensembles such that, for them, the statistical distributions of the outcomes of appropriate measurements would falsify quantum mechanics.

6. D. Bohm, Quantum Theory, Englewood Cliffs, Prentice Hall, N.J., 1951.

7. Since we assume that the choice of the apparatus settings can be made at free will, the parameters **n** and **m** do not belong to a probability space. Accordingly we prefer to avoid using the standard notation for conditional probabilities.

8. P. Suppes and M. Zanotti, 'On the Determinism of Hidden Variable Theories with Strict Correlations and Conditional Statistical Independence of Observables', in Logic and Probability in Quantum Mechanics, P. Suppes ed., Reidel Dordrecht, 445-455 (1976); B. Van Fraassen, 'The Charybdis of Realism: Epistemological Implications of Bell's Inequality', Synthese, **52**, 25-38 (1982).

9. J.P. Jarrett, 'On the Physical Significance of the Locality Conditions in the Bell Arguments', Nous, **18**, 569-589 (1984).

10. M. L. G. Redhead, Incompleteness, Nonlocality and Realism, Oxford University Press, (1987).

11. D. Lewis, Counterfactuals, Basil Blackwell Ltd., Oxford, 1986; page 7.

12. R. K. Clifton, J. N. Butterfield, and M. L. G. Redhead, 'Nonlocal Influences and Possible Worlds - a Stapp in the Wrong Direction', British Journal of Philosophy of Science, **41**, 5-58 (1990).

13. You might object that one could avoid counterfactuals by assuming as the criterion for property attribution to an individual physical system, its being in a pure state which is an eigenstate of the considered observable. Then, in our example, there are no elements of physical reality referring to σ_z prior to t_1, and the property $\sigma_z=+1$ holds after this time. However, we reply, first of all, that we consider it important to be as general as possible; and in particular, as stated in Section 1, to make use only of the predictions of the theory, without dealing with state vectors. Secondly we stress that the only reason to resort to the state vector for attributing objective properties, is the fact that only in the case of an eigenstate can one predict with certainty the outcome. So one in effect goes back to Einstein's criterion. Moreover, as is well known, to attribute a definite state vector to the measured system immediately after the measurement requires one to take a view about the nature of the measurement process, the most controversial point of quantum mechanics. Finally, as we will discuss in Section 3, in a relativistic context it turns out to be impossible to unambiguously assign a state vector to an individual physical system at a given space-time point. We will see how to deal with such a situation; but we stress that, when possible, one shoould give an analysis which allows more general hypotheses about the physical process under consideration. In this sense we consider the treatment of this Section as more general than the next Section's.

14. B. d'Espagnat, 'Nonseparability and the Tentative Descriptions of Reality', Physics Reports, **110**, 201-264 (1984).

15. Note that the converse requirement, that when a property is actually possessed measuring it leads to knowledge about its value (expressible as $\mathbf{P}_S\mathcal{A}=a(t) \supset [\mathcal{M}_S\mathcal{A}(t) \supset \mathbf{O}_S\mathcal{A}=a(t)]$), would amount to faithful measurement. We remark that this formula involves only the standard, material, implication.

16. D. Howard, 'Einstein on Locality and Separability', Studies in History and Philosophy of Science, **16**, 171-201 (1985); 'Holism, Separability and the Metaphysical Implications of the Bell Experiments', in: Philosophical Consequences of Quantum Theory, J.Cushing and E. McMullin eds., University of Notre Dame Press, Notre Dame, 224-253 (1989).

17. M. Born, ed., The Born Einstein Letters, Walker and Company, New York, 164 (1971).

18. E. Schrödinger, 'Discussion of Probability Relations between Separated Systems', Proceedings of the Cambridge Philosophical Society, **31**, 555-563 (1935).

19. G. Hellmann, 'EPR, Bell and Collapse: a Route Around "Stochastic" Hidden Variables', Philosophy of Science, **54**, 558-576 (1987); J. Butterfield, 'Causal Independence in EPR Arguments', in PSA 1990, Vol 1, A. Fine, M. Forbes and L. Wessel eds., 213-225 (1990); R. Deltete and R. Guy, 'Einstein and EPR', Philosophy of Science, **58**, 377-397 (1991).

20. A. Fine, The Shaky Game, University of Chicago Press, Chicago, 1986.

21. It goes without saying that all the following considerations hold when R and L are interchanged, i.e. that there is perfect symmetry with respect to the two space-time regions.

22. M. Born, ed., The Born Einstein Letters , Walker and Company, New York, 158 (1971).

23. Obviously, due to the symmetry between R and L, one has also to recognize that outcomes at L might depend on measurements at R.

24. J. S. Bell, 'Bertlmann's Socks and the Nature of Reality', Journal de Physique, Colloque C2, **42**, 41-61 (1981).

25. See also some arguments used in ref. 26.

26. G.C. Ghirardi, R. Grassi and P. Pearle, 'Relativistic Dynamical Reduction Models and Nonlocality', in: Symposium on the Foundations of Modern Physics 1990, P. Lahti and P. Mittelstaedt eds., World Scientific, Singapore 109-123 (1991).

27. J.P. Jarrett, 'Bell's Theorem: a Guide to the Implications', in: Philosophical Consequences of Quantum Theory, J. T. Cushing and E. McMullin eds., University of Notre Dame Press, Notre Dame, Indiana, 60-79 (1989).

28. G.C. Ghirardi, A. Rimini and T. Weber, 'Unified Dynamics for Microscopic and Macroscopic Systems', Physical Review, **D34**, 470-491 (1986); J.S. Bell, 'Are there Quantum Jumps?', in: Schrödinger-Centenary Celebration of a Polymath, C.E.W. Kilmister ed., Cambridge University Press, Cambridge, 41-52 (1987); P. Pearle, 'Combining Stochastic Dynamical State-vector Reduction with Spontaneous Localization', Physical Review, **A39**, 2277-2289 (1989); G.C. Ghirardi, P. Pearle and A. Rimini, 'Markov Processes in Hilbert Space and Continuous Spontaneous Localization of Systems of Identical Particles', Physical Review, **A42**, 78-89 (1990); G.C. Ghirardi and A. Rimini, 'Old and New Ideas in the Theory of Quantum Measurement', in: Sixty-Two Years of Uncertainty: Historical, Philosophical and Physical Inquiries into the Foundations of Quantum Physics, A.I. Miller ed., Plenum, New York, 167-191 (1990); F. Benatti, G.C. Ghirardi, A. Rimini and T. Weber, 'Quantum Mechanics with Spontaneous Localization and the Quantum Theory of Measurement', Nuovo Cimento, **100B**, 27-41 (1987).

29. P. Pearle, 'Toward a Relativistic Theory of Statevector Reduction', in: Sixty-Two Years of Uncertainty: Historical, Philosophical and Physical Inquiries into the Foundations of Quantum Physics, A.I. Miller ed., Plenum, New York, 193-214 (1990).
30. G.C. Ghirardi, R. Grassi and P. Pearle, 'Relativistic Dynamical reduction Models: General Framework and Examples', Foundations of Physics, **20**, 1271-1316 (1990).
31. Actually, as we have discussed elsewhere in detail (see refs. 26, 30, 32)), even within the standard theory the property $\mathcal{A}$=a can be attributed also when the norm in the above equation is not exactly equal but extremely close to one: $[\|P_a|\Psi,t\rangle\| \cong 1] \equiv \mathcal{P}_S\mathcal{A}=a(t)$. This is due to the fact that an outcome of a measurement is unavoidably related to the location of some macroscopic pointer, and no wave function can have a strictly compact support in configuration space. This remark allows us to make precise the vague statement "extremely close". Suppose, e.g., one measures the spin component by detecting a spot on a screen behind a Stern-Gerlach apparatus. In practical cases the separation between the two possible trajectories is overwhelmingly large with respect to the spreads of the two wave packets, so that "extremely close to one" can easily mean "larger than $1\text{-}10^{-20}$".
32. G.C. Ghirardi and P. Pearle, 'Elements of Physical Reality, Nonlocality and Stochasticity in Relativistic Dynamical Reduction Models', in: PSA 1990 Vol.II, A. Fine, M. Forbes and L. Wessel eds., East Leasing, Michingan, 35-47 (1990).
33. It is useful to recall that K.E. Hellwig and K. Kraus, 'Formal Description of Measurements in Local Quantum field Theory', Physical Review, **D1**, 566-571 (1970), put forward another proposal to make WPR covariant, viz. that the statevector collapse takes place along the past light cone having its origin at the space-time point at which the measurement occurs. If this criterion is adopted, then the particle at L would acquire an objective property at the space-time point on the past light cone from (R,t_R). The proposal is quite interesting but, as proved by Y. Aharonov and D.Z. Albert, 'States and Observables in Relativistic Quantum Field Theories', Physical Review, **D21**, 3316-3324 (1980), it meets insurmountable difficulties concerning nonlocal observables, such as, e.g., the total spin of the two particles: namely, it is not possible to assign a definite unique state vector to the hypersurfaces which cross the past light cone originating at (R,t_R).

34. G.C. Ghirardi, R. Grassi, J. Butterfield and G.N. Fleming, 'Parameter Dependence and Outcome Dependence in Dynamical Models for State Vector Reduction', Foundations of Physics, **23**, 341-364 (1993); 'Parameter Dependence in Dynamical Models for Statevector Reduction', International Journal of Theoretical Physics, to appear.
35. J. S. Bell, 'Six Possible Worlds of Quantum Mechanics', in: Proceedings of the Nobel Symposium 65: Possible Worlds in Arts and Sciences, Stockolm, 1986.
36. It is useful to recall here the most important feature of the dynamical reduction models considered in refs. 28, the feature which shows that the Dynamical Reduction Program is viable. In these models linear superpositions of particles located in different regions of space are spontaneously suppressed. The mechanism is such that the reduction time decreases by a very large factor in passing from microsystems to macroscopic ones. Thus, a macroscopic apparatus can remain in a superposition of macroscopically different states only for a very small (though not exactly zero) time interval.