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The principle of relativity, superluminality and EPR experiments.

”Riserratevi sotto coverta ...”

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Abstract. The principle of relativity claims the invariance of the results for experiments carried out in inertial reference frames if the system under examination is not in interaction with the outside world. In this paper it is analysed a model suggested by J. S. Bell, and later developed by P. H. Eberhard, D. Bohm and B. Hiley on the basis of which the *EPR* correlations would be due to superluminal exchanges between the various parts of the entangled system under examination. In the model the existence of a privileged reference frame (*PF*) for the propagation of superluminal signals is hypothesized so that these superluminal signals may not give rise to causal paradoxes. According to this model, in an *EPR* experiment, the entangled system interacts with the outer world since the result of the experiment depends on an entity (the reference frame *PF*) that is not prepared by the experimenter. The existence of this privileged reference frame makes the model non invariant for Lorentz transformations. In this paper, in opposition to what claimed by the authors mentioned above, the perfect compatibility of the model with the theory of relativity is strongly maintained since, as already said, the principle of relativity does not require that the results of experiments carried out on systems interacting with the outside world should be invariant.

1. Introduction

In the scientific community the impossibility to send superluminal signals has been accepted nearly unanimously for over a century. Generally this statement is considered a consequence of the theory of relativity. For example A. Einstein supports the impossibility to send superluminal signals in a paper of 1907 [1] and he bases his thesis exactly on claims that he considers consequences of the theory of relativity. The assumption of the non existence of superluminal signals plays a fundamental role in interpreting the results of the experiments about the violation of Bell’s inequality. In those experiments measurements on two (or more) particles of an entangled system are performed. The measurements appear correlated in a way so as to violate Bell’s inequality and the violation shows that the correlations cannot only be due to “local variables”, that is “features” present in the particles since their creation. Something else must exist, and the simplest hypothesis to imagine is that there is a sort of communication among the various parts of the entangled system. In 1982, with Aspect’s experiment, the violation of Bell’s inequality is shown in such a condition to make the exchange of subluminal signals among the various parts of the system impossible: if the “something else” is the exchange of signals between particles of the entangled system or between parts of the experimental apparatus, then those signals must necessarily travel at superluminal speed. Once the impossibility of superluminal signals is accepted, the result of the Aspect's experiment has been seen by nearly all scientists as the final defeat of the supporters of local realism: the non local aspects of the quantum mechanics, that is the existence of distant correlations without local variables or communication, have been considered incontrovertible facts, experimentally proven.

In this paper I will analyse some statements usually given in support of the impossibility to send superluminal signals. I will start from the analysis of the arguments quoted by Einstein in the above mentioned paper of 1907, arguments that, in my opinion, should be considered wrong. I will then move on to examine the theorems about the alleged paradoxicality of superluminal signals which have been reported in literature since 1950s. As we will see, those theorems show the existence of causal paradoxes in the hypothesis that the superluminal signals are produced "below decks", that is their production and propagation depend exclusively on the operation the experimenter should perform in order to produce those signals. For instance, the superluminal signal would not appear paradoxical if there was a "given" privileged reference frame for them (as the air reference is for sound signals), independent of any operation the experimenter carries out to prepare an experiment. I will then analyse a realist and local model suggested by J. S. Bell [2], later developed by P. H. Eberhard [3], D. Bohm and B. Hiley [4], according to which the correlations observed in the experiments on the violation of Bell's inequality would be due to exchanges of superluminal signals between the various parts of the entangled system; superluminal signals for which the authors hypothesize the existence of a privileged reference frame just in order to avoid causal paradoxes. The existence of such a privileged reference frame makes the model non invariant for the Lorentz transformations and this, according to the above mentioned authors, would put the model in contrast with the theory of relativity. The main purpose of this paper is specifically to disprove this latter statement: I will try to explain why that model should be considered *in perfect accord* with the theory of relativity. I will start by reconsidering the principle of relativity presented by Galileo [5] in 1630, a principle which I believe should be put as basis to the theory of relativity as given by Galileo. The principle states the invariance of the results of the experiments performed in inertial reference frames if the experimental apparatus is, in Galileo's own words, "below decks". The need to be "below decks", that is with the experimental apparatus unaffected by entities "outside"[1] the reference frame in which the experiment is being carried out, might be considered trivial (obviously possible different external influences will produce different results), nevertheless it is a necessary hypothesis in order to state the invariance of the results of the experiments. It follows that possible models non invariant for the Lorentz transformations will be in accord with the principle of relativity in the event that the non invariant effects were, at least partly, caused by entities which were not "below decks". And this is exactly the case for the model under study whose non invariant aspects are due to the presence of a privileged reference frame which is not below decks, i.e. which cannot be prepared by the experimenter.

I have already presented a study [6] in which I claim the thesis contained in this paper. Although some parts of this paper are repetitions of others already presented in [6], I will try here not to dwell on those parts already developed in details in [6] but to focus on the ideas only hinted in my previous study.

[1] I believe that the concept of "below decks" introduced by Galileo should be further developed. In my opinion everything the experimenter can access should be considered "below decks". Entities the experimenter cannot affect are not below decks even if they are "present" inside the reference frame in which the experiments are performed. It is not to be considered below decks a possible privileged reference frame (like the one which, in the model examined in this paper, is assumed to support the propagation of superluminal signals) which cannot be either shielded or dragged, i.e. that can't be "prepared" by the experimenter at his will.

2. Conventionality of simultaneity

The issue of the conventionality of the simultaneity emerged with the appearance of the theory of relativity. Among the main champions of the conventionalist thesis there was definitely Hans Reichenbach who presented his ideas in several papers, among which *Philosophie der Raum-Zeit-Lehre* [7] of 1928 is probably the most famous. The debate became passionate only some years later, as M. Jammer pointed out [8] (page 192):

> It was only in the late 1950s that Reichenbach's philosophy of space and time, and his thesis of the conventionality of simultaneity, found the attention they deserve.

In my opinion, to this day, a considerable part of the scientific community ignores the principal points of the debate about the conventionality of simultaneity and we may often read scientific papers in which the anticonventionalist thesis is implicitly taken for granted. Such a tacit assumption could only be accepted if the debate on the issue had ended with the confutation of the conventionalist thesis, which is surely not true:

> The debate about conventionality of simultaneity seems far from settled, although some proponents on both sides of the argument might disagree with that statement.[9]

I believe that the studies in which the anticonventionalist thesis is implicitly assumed must be considered incorrect. We will later see remarkable examples of studies to be considered wrong in my opinion. Let's first sum up the terms of the matter.

2.1. The terms of the matter

In his very famous article of 1905 [10], A. Einstein initially assigns a triplet of coordinates $\vec{x} = (x_1, x_2, x_3)$ to every single point in an inertial reference frame by using rigid rulers. Then, in order to describe the motion of a body in the given reference frame, he sets a clock in every point and the motion of the body is described by the instant t marked by the clock set in $\vec{x}$ in the moment the body is in $\vec{x}$. To make this description physically relevant (so that, for example, the motion could be reproduced through the description) it is necessary *to synchronize* the various clocks set in the various points of the reference frame. Einstein clearly states his opinion on this matter pointing out that the synchronization is set *by definition*[2] establishing that the velocity of light from a certain point A towards a point B is the same as the velocity of light from B towards A, i.e. calling t_A the instant marked by the clock set in A when a light beam starts from A and t'_A the instant marked by the same clock when the beam returns in A after being reflected in B, we say that the clock in B is synchronized with the one in A if it marks the instant

$$t_B = t_A + \frac{t'_A - t_A}{2} \qquad (1)$$

at the moment the beam is reflected in B. The "time" thus defined, that is the set of instants marked by the clocks fixed in the reference frame and synchronized according to (1), is called by Einstein "the time of the stationary system". Hans Reichenbach will later stress the conventional aspect of the "time of the stationary system" being the synchronization of the clocks conventional: the physical content of the relativity would not change if we put

$$t_B = t_A + \varepsilon \left(t'_A - t_A \right), \qquad (2)$$

with ε free parameter, instead of (1). By choosing the (2) a non standard synchronization is said to be adopted whereas the (1), i.e. the particular case $\varepsilon = 1/2$, results in what it is called standard synchronization (that is the one Einstein adopted in his 1905 study). The time interval $t'_A - t_A$ is not conventional, since it is the result of a measurement (the one taken by the clock

[2] The words "durch Definition" are highlighted in the original text.

fixed in A from the moment the light beam starts from A to the moment it returns in A after being reflected in B); however, the interval $t_B - t_A$ which depends on the value chosen for ε is conventional. Reichenbach also points out that the second postulate of the special relativity does not claim that the speed of light from A to B is the same as the one we find from B to A (the speed from one point to the other is called one-way) as this statement does not have physical content, that is it is not experimentally verifiable, since the one-way speed is a conventional entity. The second postulate states that the back and forth speed of light is always the same, that is if two lightbeams start simultaneously from A, to return there after reflecting one in B and the other in C, then the two lightbeams will get back simultaneously if $\overline{AB} = \overline{AC}$. The back and forth speed of light is indicated by c. For instance in (2), we can set $t'_A - t_A = \frac{2\overline{AB}}{c}$. Actually Reichenbach does not leave the parameter ε completely free, he sets $0 < \varepsilon < 1$ so that, from his point of view, the time order of casually linked events always agrees with the causal order, i.e. it is always $t_E > t_C$ if the cause occurs in the point C when the clock fixed in C is marking the instant t_C and the effect occurs in the point E when the clock fixed in E is marking the instant t_E. Reichenbach obtains this result assuming the non existence of superluminal signals, assumption he considers "not an arbitrary assumption but a physical law based on experience. [...] In order to accelerate a body to the velocity of light, an infinite supply of energy would be required, and it is therefore physically impossible for any object to attain this speed" ([7] pag. 203). However, the fact that it is impossible to accelerate a mass particle to the velocity of light does not imply that superluminal signal could not exist. A superluminal signal could start as such and always remain superluminal until it is absorbed. It does not necessarily need to be generated as subluminal to become superluminal after acceleration. Mass particles must necessarily have subluminal velocity for the reason given by Reichenbach quoted above (they would need infinite energy to reach the light velocity); however, nothing imposes to associate mass to a superluminal signal. The condition $0 < \varepsilon < 1$ is no longer imposed in modern studies, at least not by all the supporters of the conventionalist thesis. For example in [11], page 130, we can read

> it should be pointed out that one should distinguish "spatially coincident causality" from "distant causality"; there is no contradiction if an occurrence at P at time t causes another occurrence at Q≠P at time $t' < t$ because the two different times are measured at spatially different locations. Indeed, as mentioned in Section 1.5.1, such apparent inconsistencies are familiar consequences of the International Date Line for airline travellers.
>
> The rejection of a temporal ordering in distant causality espouses a point of view in which time at any spatial point flows independently of time at other points, with there being no canonical prescription for the way one links the times at spatially separated points.

In substance, the (2) could be generalized in

$$t_B = t_A + \frac{\overline{AB}}{c} + \phi\left(\vec{x}_B\right) - \phi\left(\vec{x}_A\right) \tag{3}$$

and there is no "canonical prescription" for the function $\phi\left(\vec{x}\right)$. In particular, the time sequence between two distant events can be set as wanted subject to the appropriate choice of the function $\phi\left(\vec{x}\right)$. But the time order of distant events has nothing to do with the causal order. Causally linked events obviously maintain their causal link regardless of our descriptive choices. The example of the planes travelling westwards quoted in [11] in the extract above is quite clear: departure and arrival are causally linked being the former the cause and the latter the effect. This causal link remains obviously even if the departure takes place in New Zealand at three o'clock (time given by the clocks fixed in New Zealand) and the arrival in Rome at two o'clock

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(time marked by the clocks set in Rome). By choosing the (2) or the (3), instead of (1), there would only be descriptive complications although the physical content of the theory would be unaltered. In other words, it is not nature which "imposes" (1), it is us who choose it to deal with easier descriptions; we could as well choose the (2), or the (3), without facing any substantial problem since descriptive simplicity does not have any physical value. As an example, in the paragraph 2.3.3 of [11] we can find the equations of electromagnetism if we choose to synchronize employing (3) with $\phi(\vec{x}) = -\vec{k} \cdot \vec{x}$ being $\vec{k}$ a generic constant vector.

As presented above, the conventionalist thesis is not universally accepted at present. Surely it is not universally rejected, either. It is not my intention to join the debate and I refer the readers interested in the topic to the quoted references [8, 9, 11] as well as to the substantial bibliographical notes given in those papers. I just confine myself to offer some quotations and some final remarks.

In 1928 Albert Einstein published a review [12] of Reichenbach's book *Philosophie der Raum-Zeit-Lehre* [7] where he also said:

> special care has been taken to ferret out clearly what in the relativistic definition of simultaneity is a logically arbitrary decree and what in it is a hypothesis, i.e., an assumption about the constitution of nature. (quoted in [8] pag.181).

In the famous book *Relativity; the special and the general theory, a popular exposition* [13] Einstein wrote also:

> That light requires the same time to traverse the path A→M as for the path B→M [M being the midpoint of the distance AB] is in reality neither a supposition nor a hypothesis about the physical nature of light, but a stipulation which I can make of my own free will in order to arrive at a definition of simultaneity.

Marco Mamone Capria writes his ideas critical of the conventionalist thesis in a study of 2001 [14] where he also states (page 777):

> The debate on this issue has been going on for decades without quite reaching a satisfactory conclusion, though it appears that the CS [Conventionality of Simultaneity] thesis has somewhat conquered the status of a majority view - not always for good reasons, as we shall see.

So, according to a critic of the conventionalist thesis, this thesis "appears the majority view."

My personal opinions at the end of this paragraph represent the introduction to the following one. The time order between distant events induced by any synchronization can't be associated to the causal order without supporting such an association with a demonstration. For example we could follow Reichenbach's demonstration mentioned above: we could believe that the non existence of superluminal signals is experimentally verified and on the basis of this assumption we would demonstrate that the causal order between distant events is always in accord with the time order brought about through standard synchronization, as well as through all synchronizations induced by the (3) under the condition $\left|\vec{\nabla}\phi\right| < 1$. Certainly, because of a clear problem of circularity, the non existence of superluminal signals cannot be demonstrated simply because those signals might travel "backwards in time", that is they could give rise to effects in a certain point E at the instant t_E, since the cause occurred in a point $C \neq E$ at the instant $t_C > t_E$. The causal order is definitely not conventional. The time order between distant events brought about through standard synchronization, as well as through any other synchronization, arises like a conventional order to which it is a mistake to give the value of causal order without supporting it with any justification. We will see that outstanding examples of such mistakes can be often found in literature. The conventional origin of time order is ignored and an anticonventionalist approach is implicitly and often unconsciously taken: standard synchronization is given the status of "correct" synchronization and the time order induced through the standard synchronization is given the value of causal order.

2.2. Some mistakes

2.2.1. Einstein. In 1907 Einstein publishes a study in which he introduces a demonstration about the impossibility of the existence of superluminal signals later recalled by numerous authors such as: Tolman [15] (pagg. 54-55), Pauli [16] (pag. 16), Von Laue [17] (pag. 70). Adopting the standard synchronization, Einstein analyses two events, *caus* and *eff*, which are described through the coordinates $caus = (ct_c, x_c)$ and $eff = (ct_e, x_e)$ in a given inertial reference frame Σ. Einstein hypothesizes that it is

$$ct_e > ct_c \tag{4}$$

and that the two events are "space like", that is

$$c^2 (t_e - t_c)^2 - (x_e - x_c)^2 < 0. \tag{5}$$

From the (4) and (5), supposing it is $x_e > x_c$, it follows

$$x_e - x_c > ct_e - ct_c. \tag{6}$$

It is hypothesized that the two events are linked causally, i.e. *eff* is the effect and *caus* the cause. At this point Einstein describes the two events in a new inertial reference frame, Σ', in motion at the speed βc in respect to Σ, with $|\beta| < 1$. The coordinates of the two events in the reference frame Σ', $caus = (ct'_c, x'_c)$ and $eff = (ct'_e, x'_e)$, are obtained by using standard Lorentz transformations, i.e. Lorentz transformations in the form they take if standard synchronization is assumed[3]. In particular it is obtained

$$ct'_e - ct'_c = \gamma \left[(ct_e - ct_c) - \beta (x_e - x_c) \right] \tag{7}$$

with $\gamma = 1/\sqrt{1-\beta^2}$. From the (7) it is obtained:

$$\beta > \frac{ct_e - ct_c}{x_e - x_c} \Longleftrightarrow ct'_e < ct'_c \tag{8}$$

that is, considering the (6), if the two events are "space like", then it is always possible to obtain appropriate values of β, with $|\beta| < 1$, for which the time order between the events *eff* and *caus* will be discordant between Σ and Σ'. In the reference frame Σ' the cause *caus* is associated to a greater instant than the one associated to the effect *eff*. This is deemed impossible by Einstein (and by many authors who have resumed his demonstration) and hence it can be inferred that space like events can't be linked causally. Einstein's words are the following (in the translation quoted in [18]):

> If, as we have assumed $W > c$ [i.e. (6) in our notations], one can always choose v [β] such that $T < 0$ [$ct'_e < ct'_c$]. This result means that we would have to consider as possible a transfer mechanism whereby the achieved effect would precede the cause. Even though this result, in my opinion, does not contain any contradiction from a purely logical point of view, it conflicts with the character of all our experience to such an extent that this seems sufficient to prove the impossibility of the assumption $W > c$

[3] Assuming a certain non standard synchronization, Lorentz transformations change their form keeping their physical content. In [11] (pag. 129) there is the form taken by Lorentz transformations between two reference frames Σ and Σ' in which it is synchronized through the (3), with $\phi(\vec{x}) = -\vec{k} \cdot \vec{x}$ in Σ and $\phi(\vec{x}) = -\vec{k}' \cdot \vec{x}$ in Σ', being $\vec{k}$ e $\vec{k}'$ generic constant vectors.

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In 1905 Einstein defines conventionally the "time of the stationary system" then, in 1907, it is precisely on it that he bases his statement "the achieved effect would precede the cause". As if the causality might be derived from a "stipulation which I can make of my own free will", in the words Einstein himself will use, as we have seen, in 1924. It is like defining conventionally a certain synchronization for the clocks fixed on the Earth and then establishing that it is impossible that a plane departed from New Zealand at three o'clock arrives in Rome at two because, if that happened, "the achieved effect would precede the cause". Naturally an anticonventionalist approach might always be assumed and then claim that the clocks fixed on the Earth are not synchronized in the "correct" way and that if all the clocks were set at GMT, it would then be true that neither planes nor other signals of any kind departed from a certain point at the instant t_c in a given inertial reference frame Σ could reach another point at an instant $t_e < t_c$; nevertheless, such a statement would have to be demonstrated. Anyway Einstein never assumes an anticonventionalist approach; I would therefore say that the demonstration given above must necessarily be considered incorrect.

2.2.2. The principle of reinterpretation. From the 1960s studies [19–23] have been introduced in scientific literature in which the existence of superluminal particles (called "tachyons") is hypothesized and they claim that it is possible to overcome the "paradox" we have just seen on the basis of a principle they call principle of reinterpretation. The alleged paradox consists in the fact that it is always possible to find an appropriate reference frame Σ' so that, if a tachyon travels "forward in time" in the reference frame Σ, it will then travel "backward in time" in Σ'. It is totally overlooked the fact that the expressions "forward in time" and "backward in time" are based on the "time of the stationary system", in its turn defined through a synchronization (the standard one) assumed conventionally and those expressions are given as if they had an evident physical meaning. In particular, as Einstein had already done in his study in 1907, it is assumed, as something not to be justified at all, that the travels "backward in time" are not possible. This time, however, Einstein's statement is not deduced from this assumption. This time a mistake is made which, in my opinion, is far more serious. A principle is stated, on the basis of which cause and effect would be "written" in the time order of the "time of the stationary system" and if this order in Σ' is discordant from the one we have in Σ, then in Σ' the role of cause and effect must be "reinterpreted". Namely, the event which is cause in Σ is "reinterpreted" as effect in Σ'. The authors believe they can justify this principle on the basis that the tachyons travelling "backward in time" are always associated to negative energy and once they have been "reinterpreted", they would travel "forward in time" with positive energy. Personally I believe that the "principle of reinterpretation" is a true violence to the concept of causality. The causal order has physical value and it is the time order induced through any synchronization which must be "reinterpreted", if the existence of tachyons is to be hypothesized.

2.2.3. The multisimultaneity. In 1997 A.Suarez and V. Scarani [24] proposed an experiment aimed at evaluating a description of the phenomenon of the entanglement alternative to the one given by the standard quantum mechanics. The name multisimultaneity was given to such alternative description. The proposed experiment was then carried out by the Gisin group [25] and the result was in perfect accord with the standard quantum mechanics.
The issue is summarised perfectly on the webpage [26] from which some excerpts are quoted below:

> Entangled particles behave as if there was a *faster than light connection* between them. [...]
>
> I was strongly convinced that it should be possible to give a time-ordered causal explanation of nonlocal correlations, in terms of "before" and "after". Indeed, such

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> a description is very well possible in conventional Bell experiments, in which all apparatuses are standing still in a laboratory frame. Since the emission time of the photons is not exactly the same, and the fibers guiding the photons from the source to the measuring devices don't have exactly the same length, according to the clock defined by the laboratory's inertial frame, one of the measurements always takes place before the other, and the particle arriving later can be considered to take account of the outcome of the one arriving before.[...]
>
> But what about experiments with moving apparatuses in which several relevant frames are involved? In this case, different clocks watch the arrival times, and what is "after" according to the laboratory clock may become "before" according to one moving clock. Then, it is possible to define other time orderings: If each measuring device in its own reference frame is the first to select the output of photons, we have before-before timing. If each measuring device in its own reference frame selects the photon output after the other, we have after-after timing. Is it also possible to give a time-ordered causal explanation for relativistic experiments using apparatuses in motion? I assumed it was, and developed an alternative nonlocal description termed "multisimultaneity", in which the time-ordered description of the nonlocal correlations extends to experiments with before-before and after-after timings. Consider, for instance, experiments in which the measuring devices are in motion in such a way that each of them, in its own reference frame, is the first to select the output of photons (before-before timing). Then each particle's choice will become independent of the other's and, according to multisimultaneity, the nonlocal correlations should disappear. In contrast, quantum mechanics requires that the particles stay non local, correlated independent of any timing, even in such a before-before situation.

Here too, the identity between causal order and time order is taken for granted without giving any supporting justification. It is hypothesized that the nonlocal correlations can have a "causal explanation", that the two measurements can be ordered causally with one occurring "before" the other, but the "before" is established by the "time of the stationary system". Here too, the causal order is "forced" to respect the time order induced through standard synchronization. So much to assume that the causal order must break up (bringing about the disappearance of nonlocal correlations) when the time orders of the two measurements in the corresponding reference frame are discordant. Here too, constraints are put to an order with physical content, the causal order, to safeguard an order which starts as conventional (and which continues, even after its appearance, to be considered necessarily conventional according to what "appears to be the majority view" among the people who publish papers on this topic).

3. Superluminal signals and causal paradoxes

The modern texts present the theorem about the link between superluminal signals and causal paradoxes in a different way from the one mentioned in the paragraph 2.2.1. What is considered paradoxical is the possibility to communicate with one's past [27] (pp. 52-53), [28] (pp. 186-189), [29] (p. 21), [30] (pp. 274-275), [31] (p. 55). This possibility would give rise to undeniable paradoxes which clearly have nothing to do with the procedure we decide to follow to synchronize the clocks (even if I decided to turn my clock back 48 hours, yesterday would still remain yesterday, it would not become tomorrow). The theorem presented by Møller [27] has a more general form; however, since I have already examined it in detail in [6], I will here analyse only the simplified form commonly quoted [28–31]. Recalling the example seen in the paragraph 2.2.1, we put

$$\beta_t \equiv \frac{x_e - x_c}{ct_e - ct_c}. \tag{9}$$

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We can hypothesize that the events *caus* and *eff*, which in Σ have coordinates $caus = (ct_c, x_c)$ and $eff = (ct_e, x_e)$, are respectively emission and detection of a superluminal signal which has speed equal to $\beta_t c$ in Σ (from the (4)-(6) follows $\beta_t > 1$). We can call S_{go} this signal. From Lorentz transformations we obtain that, in the reference frame Σ', in motion at speed βc respect to Σ, the event *eff* has coordinates $eff = (ct'_e, x'_e)$ with

$$\begin{cases} ct'_e = \gamma\,(ct_e - \beta x_e) \\ x'_e = \gamma\,(x_e - \beta ct_e) \end{cases} . \tag{10}$$

At this point we *assume* that, in coincidence with the event *eff*, it is possible to send a new superluminal signal, S_{back}, in the negative direction of *x'*, which has in Σ' speed $-\beta_t c$. More generally we could assume that,

(i) if it is possible to send a superluminal signal which has in Σ speed $\beta_t c$, then, in any other inertial reference frame, it must be possible to emit superluminal signals in any directions which have the same speed $\beta_t c$.

It is commonly believed that this assumption is just the direct consequence of the relativity principle. In Σ' the time law of the superluminal signal S_{back} is

$$x' = x'_e - \beta_t\left(ct' - ct'_e\right), \tag{11}$$

and from it, through Lorentz transformations, the time law of S_{back} in Σ can be easily obtained:

$$x = x_e - \frac{\beta_t - \beta}{1 - \beta\beta_t}\,(ct - ct_e)\,. \tag{12}$$

Considering the (9), from the (12), the coordinates of a new event, eff_1, associated with the arrival of S_{back} in x_c, can be obtained:

$$eff_1 = \left(ct_{e_1} = ct_c + \frac{2\beta_t - \beta\left(1 + \beta_t^2\right)}{\beta_t\,(\beta_t - \beta)}\,(x_e - x_c)\,, x_c\right). \tag{13}$$

So we have the chain of the following three events which are in causal order:
caus: departure of the signal S_{go} from the point which has abscissa x_c in Σ;
eff: arrival of S_{go} in the point which has abscissa $x_e > x_c$ in Σ, and simultaneous departure from the same point of the signal S_{back};
eff_1: arrival of S_{back} in the point which has abscissa x_c in Σ, i.e. the point from which S_{go} had departed.
If the instant ct_{e_1}, defined in the (13), could be less than ct_c, then it would be an evident causal paradox: in the point which has abscissa x_c in Σ, the effect eff_1 would occur "before" the cause *caus*. An observer set in Σ in the point with abscissa x_c could send a question through the signal S_{go} when his clock marks 3 and receive the answer through S_{back} when his clock marks 2. Here the situation is clearly different from the one described in the paragraph 2.2.1. Here the conclusion is totally independent of the procedure chosen to synchronize the clocks since now we do not compare instants marked by different clocks. Rather, instants marked by a single clock are compared, the clock fixed in Σ in the point with abscissa x_c. From the (13) it is easily obtained

$$ct_{e_1} < ct_c \Longleftrightarrow \beta > \frac{2\beta_t}{1 + \beta_t^2} \tag{14}$$

and, being $\frac{2\beta_t}{1+\beta_t^2} < 1 \forall \beta_t$, it follows that it is always possible to determine appropriate reference frames Σ', in motion at speed βc respect to Σ (with $|\beta| < 1$), so as to make the situation described above paradoxical. Hence we can say that it would always be possible to give rise to causal paradoxes if superluminal signals existed.

This demonstration is based on the assumption (i) reported above. We could say that it is based on the principle of relativity if we accepted that the (i) is the necessary consequence of the principle of relativity. If we accepted this approach we would have to say that, in order to make superluminal signals which don't give rise to causal paradoxes possible, we would have to deny the principle of relativity, thus questioning all the theories based on that principle like, for example, the theory of relativity which has exactly the principle of relativity among its postulates. In the following paragraph I will try to illustrate the reasons why, in my opinion, this approach is untenable: the assumption (i) can be violated without undermining even marginally the principle of relativity in any way.

4. The Principle of Relativity

The principle of relativity is stated by Galileo in *Dialogo Sopra i due Massimi Sistemi del Mondo* [5]:

> Shut yourself up with some friend in the main cabin below decks on some large ship, and have with you there some flies, butterflies, and other small flying animals. Have a large bowl of water with some fish on it; hang up a bottle that empties drop by drop into a narrow-mouthed vessel beneath it. With the ship standing still, observe carefully how the little animals fly with equal speed to all sides of the cabin. The fish swim indifferently in all direction; the drops fall into the vessel beneath; [...] When you have observed all these things carefully (though there is no doubt that when the ship is standing still everything must happen in this way), have the ship proceed with any speed you like, so long as the motion is uniform and not fluctuating this way and that. You will discover not the least change in all the effects named, nor could you tell from any of them whether the ship was moving or standing still.

In modern words, Galileo claims the invariance of the results for the experiments carried out in inertial reference frames[4]. Galileo points out that, in order to obtain the thesis, the experiments must be carried out "below decks". Galileo *does not* maintain the equivalence of all inertial reference frames! If we repeat a certain experiment on two different ships whose "motion is uniform and not fluctuating this way and that", we might as well obtain *different outcomes* if the experiment were not carried out "below decks" on both ships. The external environment, the one not directly connected with the experimental apparatus, might, as a matter of principle, interact somehow with some parts of the system causing asymmetries (the interaction with the outside will not necessarily be the same in both cases). For example, if a ship was aligned with the vertical and the other was leaning, even if both moved with uniform motion, experiments connected with gravity would have different results in the two ships: in one case a ball left stationary on a table would stay stationary, in the other it would start to roll. Although Galileo was not aware at his time, the gravitational effects result exactly from interactions with the outside which are not shielded[5]. We are not "below decks" in relation to gravitational interactions.

I believe that the concept of "below decks" should have the following meaning: every experiment on a certain physical system always consists in the preparation of some entities (causes) and the observation of some results from measurement operations (effects). It might be that the evolution

[4] After E. Fabri [32], with the words "reference frame" I mean a laboratory, a room, inside which all the instruments necessary to carry out any experiment are available (see also [6] par. 2).

[5] Here we are obviously using the metaphor of Galileo's ship from a point of view preceding the advent of the general relativity. According to the general relativity Galileo's ship cannot be considered an inertial reference frame since it is not in free fall.

of the physical system depends *only* on the causes appropriately prepared by the experimenter and, if that is true, then the outcomes of the measurement operations will always be the same. Being "below decks" means having shielded the system from every possible interaction with the external environment. In such a condition the evolution of the system will only depend on what is inside the reference frame, that is on what the experimenter can affect and has consequently been able to prepare appropriately. By giving this meaning to the concept of "below decks", claiming the validity of the principle of relativity would amount to claiming the validity of the causal determinism: if the same causes are repeated, the same effects will be obtained, regardless of "where" and also "when" the repetition of the causes takes place.

If a certain model should hypothesize the existence of a certain reference frame, privileged relatively to a certain set of phenomena *Ph*, then we obviously could not say that the model violates the principle of relativity. We should only not require the invariance for those experiments in which the phenomena *Ph* are somehow involved.

We might wonder if the principle of relativity, in the form above ascribed to Galileo, can be considered one of the postulates of the theory of relativity. In *The Meaning of Relativity* Einstein claims [33]:

> If K is an inertial system, then every other inertial system K' which moves uniformly and without rotation relatively to K, is also an inertial system; the laws of nature are in concordance for all inertial systems. This statement we shall call "principle of special relativity".

With "the laws of nature" Einstein clearly means all the natural laws, therefore also the law about the propagation of possible superluminal signals. Definitely this principle would be violated if we could demonstrate the existence of superluminal signals ruled by an "aether" which would determine a privileged reference frame for those signals. To hypothesize the existence of a privileged reference frame for the superluminal signals is the easiest way to imagine that the condition (i) does not count without incurring in the causal paradoxes examined above. The question we are posing is the following: in order to develop the theory of relativity do we need a "strong" postulate like the one stated by Einstein or a more general one like Galileo's is sufficient? Is the invariance to be required for all physical laws or only for those related to phenomena which can be reproduced below decks? In my opinion the answers are compulsory: in the form used by Einstein, the principle can be considered correct only if we imply that the reference frames K and K' are immersed in an environment without any role in the "laws of nature" we are speaking about. In other words, the principle stated by Einstein can be considered correct only if we imply that K an K' are "below decks". Following Einstein in the development of the theory of the special relativity we can see that he actually never uses the "strong" form of the principle of relativity. He assumes the non existence of a privileged reference frame for electromagnetic phenomena; he then deals with rulers and clocks as if there was not a privileged reference frame for them either, and on that basis he obtains a series of results. In substance we could say that the physics we do with rulers, clocks and electromagnetic phenomena is physics performed "below decks", therefore, on the basis of the principle of relativity, it will be physics for which the invariance of the results will be required. There will naturally be also other physics which can be performed below decks, for which the invariance will be required, but in no way does the principle of relativity impose that *all* physics must have the possibility to be performed below decks. The possible discovery of phenomena which cannot be reproduced below decks would leave unaltered the results of the theory of relativity, e.g. the fact that the descriptions of a phenomenon on two different inertial reference frames are linked through Lorentz transformations and not Galileo's ones.

The conclusion to be drawn is, in my opinion, inevitable: hypothesizing the existence of a privileged reference frame for the propagation of superluminal signals not only makes it possible to overcome cleverly the problems linked to the causal paradoxes mentioned above, it also makes those signals perfectly compatible with the theory of relativity. We will see in the next chapter that, on these basis, it is possible to build a model which enables us to represent *EPR* phenomena through a realist and local description.

5. A realist and local model for *EPR* phenomena

In an interview [2] John S. Bell gives the following answers to questions about Aspect's experiment:

> You can imagine that there is a preferred frame of reference, and in this preferred frame of reference things do go faster than light. But then in other frames of reference when they seem to go not only faster than light but backwards in time, that is an optical illusion [...] But that is certainly the cheapest solution. Behind the apparent Lorentz invariance of the phenomena, there is a deeper level which is not invariant. [...]
>
> The reason I want to go back to the idea of an aether here is because in these EPR experiments there is the suggestion that behind the scenes something is going faster than light [...]
>
> It introduces great problems, paradoxes of causality and so on. And so it' s precisely to avoid these that I want to say there is a real causal sequence which is defined in the aether (pagg 48-50).

Some years later P. H. Eberhard [3] and D. Bohm and B. Hiley [4] will present a model taking in Bell's suggestions. In [6] I have already quoted extracts from all these authors examining in details the various aspects of the model of which I will here only present the essential points. I will also introduce the main features the experiments designed to test the model must have. After N. Gisin [34], we will call these experiments "Salart-type" experiments.

The fundamental idea is that the collapse of the wave function is a process which originates in the point where a certain measurement is taken. If we imagine an *EPR* experiment on an entangled system with two particles, normally one will be measured before the other. From the point where the first measurement occurs a wave immediately propagates, a superluminal signal, which can reach the other particle before the corresponding measurement is performed on it. If that happens, the two measurements appear correlated according to what the quantum mechanics predicts, that is a violation of Bell's inequality occurs. The two measurements, instead, will not be correlated according to the predictions of the quantum mechanics (i.e. there will be no violation of Bell's inequality) if the "second" measurement is performed when the second particle still has not been hit by the superluminal signal which originated in the point in which the "first" measurement was taken[6]. Recent theoretical results [35, 36] show that, assuming the correctness of the model, even if we imagined these superluminal signals as "hidden", inaccessible to the macroscopic world, it would be possible to communicate at superluminal velocity: "the models based on hidden influences propagating at a finite speed $v > c$" allow "superluminal communication [which] does not require access to any hidden physical quantities, but only the manipulation of measurement devices"[35].

In order to overcome the problems connected to the causal paradoxes examined above the existence of a certain reference frame Σ' is hypothesized, which proves privileged as to the propagation of superluminal signals. The "privilege" consists in the fact that only in Σ' the propagation of the superluminal signals proves to be isotropic, that is, given two generic point A and B set in Σ', if from the point A a light beam Fl and a superluminal signal Ft are sent simultaneously, then Ft will reach B with a certain advance respect to Fl and the advance will be directly proportional to the length of the segment $\overline{AB}$. In particular the advance will prove independent of the direction of the segment $\overline{AB}$. In substance, it is hypothesized that an aether

[6] Actually in such a case it does not make much sense to order the two measurements since there is no causal relation between them. Neither measurement affects the other.

analogous to the one we have for sound signals exists for superluminal signals. If we hypothesize the standard synchronization in Σ' we can say that a superluminal signal has in Σ' a certain speed $\beta_t c$, with $\beta_t > 1$, regardless of its direction of propagation. The description of an *EPR* experiment on an entangled system with two particles proves particularly simple in Σ'. We can call e_A and e_B the events associated to the two measurements. The coordinates associated to the two events in the reference frame Σ' (in standard synchronization) are

$$\begin{cases} e_A : (ct'_A, \overrightarrow{x}'_A) \\ e_B : (ct'_B, \overrightarrow{x}'_B) \end{cases} . \tag{15}$$

In order to avoid that the two measurements may give rise to a violation of Bell's inequality the superluminal signal starting from $\overrightarrow{x}'_A$ at the instant ct'_A is to arrive in $\overrightarrow{x}'_B$ when the event e_B has already taken place, that is it has to be:

$$ct'_B < ct'_A + \frac{|\overrightarrow{x}'_B - \overrightarrow{x}'_A|}{\beta_t c}. \tag{16}$$

In the (16) the hypothesis of isotropy has been used, that is the fact that in Σ' the superluminal signals have speed $\beta_t c$ in any direction. In order not to have a violation of Bell's inequality also the superluminal signal starting from $\overrightarrow{x}'_B$ at the instant ct'_B is to arrive in $\overrightarrow{x}'_A$ when the event e_A has already occurred:

$$ct'_A < ct'_B + \frac{|\overrightarrow{x}'_A - \overrightarrow{x}'_B|}{\beta_t c}. \tag{17}$$

The (16) and (17) are summed up in

$$\left|ct'_B - ct'_A\right| < \frac{|\overrightarrow{x}'_B - \overrightarrow{x}'_A|}{\beta_t c}. \tag{18}$$

To verify the validity of the model under examination an *EPR* experiment should be performed in a condition so as to satisfy the (18) and the prediction of the model is that if the (18) is satisfied then the measurements will satisfy Bell's inequality in contrast with the predictions of quantum mechanics. The (18) will be surely satisfied if the two measurements are simultaneous (in standard synchronization) in Σ':

$$\Delta ct' \equiv ct'_B - ct'_A = 0. \tag{19}$$

However, experimental uncertainties will never allow that the (19) is verified exactly; it will always be

$$\left|\Delta ct'\right| < \delta' \tag{20}$$

where δ' is the experimental uncertainty with which the instants ct'_A and ct'_B can be equalized. From the (18) we gather that the experiment would allow the verification of the effect hypothesized by the model (the verification of Bell's inequality in contrast with the hypothesis of quantum mechanics) if

$$\beta_t c < \beta_{t,max} c \equiv \frac{|\overrightarrow{x}'_B - \overrightarrow{x}'_A|}{\delta'}. \tag{21}$$

Any experiment would give a null result if the superluminal signals were "too fast" i.e. if $\beta_t > \beta_{t,max}$. To improve an experiment, that is to enable to investigate increasingly greater values of β_t, the value of $\beta_{t,max}$ defined in the (21) must be made as great as possible, that is the farthest possible simultaneous measurements ($|\overrightarrow{x}'_B - \overrightarrow{x}'_A|$ great) must be performed with the smallest possible uncertainty about the simultaneity (δ' small).

Obviously the privileged reference frame Σ' is unknown and any experiment will be performed in the reference frame of the laboratory Σ which will move at a certain unknown speed $\overrightarrow{\beta} c$ in relation to Σ'. In Σ the coordinates associated to the events e_A and e_B will be:

$$\begin{cases} e_A : (ct_A, \overrightarrow{x}_A) \\ e_B : (ct_B, \overrightarrow{x}_B) \end{cases} . \tag{22}$$

From the Lorentz transformations we gather important information on the conditions to be followed in Σ so that the measurements are simultaneous in Σ'. Particularly we obtain

$$\Delta ct' = \gamma \left(\Delta ct + \overrightarrow{\beta} \cdot \Delta \overrightarrow{x} \right) \tag{23}$$

with $\gamma = {}^1/\sqrt{1-\beta^2}$, $\Delta ct \equiv ct_B - ct_A$ e $\Delta \overrightarrow{x} \equiv \overrightarrow{x}_B - \overrightarrow{x}_A$. To annul $\Delta ct'$ both addends to the right of the (23) can be annulled, however, being $\overrightarrow{\beta}$ unknown, it is not known the direction the vector $\Delta \overrightarrow{x}$ should have so as to annul the product $\overrightarrow{\beta} \cdot \Delta \overrightarrow{x}$. This problem can be solved taking advantage of the Earth's daily rotation: if we place the vector $\Delta \overrightarrow{x}$ in direction East-West, regardless of the direction of $\overrightarrow{\beta}$, every day there will always be two instants which will give $\overrightarrow{\beta} \cdot \Delta \overrightarrow{x} = 0$. The experimental procedure to comply with will then be the following: the points in which the measurements will be carried out, $\overrightarrow{x}_A$ and $\overrightarrow{x}_B$, are placed in direction East-West and simultaneous measurements (in standard synchronization) in Σ are performed continuously at least for 12 hours. We wait for the "right" instant, the one which should give rise to correlations which do not violate Bell's inequality. Every pair of measurements will have a time duration δt. In Σ too we will obviously have a certain experimental uncertainty δ about the simultaneity of the two measurements, i.e. it will be $\Delta ct = 0 \pm \delta$. Given $\overline{\rho} \equiv \frac{\delta}{|\Delta \overrightarrow{x}|}$ it is obtained [37, 38]:

$$\beta_{t,max} = \sqrt{1 + \frac{(1-\beta^2)(1-\bar{\rho}^2)}{\left(\bar{\rho} + \beta \sin\chi \sin\frac{\pi \delta t}{T}\right)^2}} \tag{24}$$

being $T = 24h$, $\beta = \left|\overrightarrow{\beta}\right|$ and χ the angle between $\overrightarrow{\beta}$ and the polar axis. From the (24) we obtain $\lim_{\beta \to 0^+} \beta_{t,max}(\beta) = {}^1/\bar{\rho}$ and $\lim_{\beta \to 1^-} \beta_{t,max}(\beta) = 1$. The minimum value of $\beta_{t,max}$ is obtained for $\chi = {}^\pi/2$, besides, two regimes can be identified for the function $\beta_{t,max}(\beta, \chi = {}^\pi/2)$:
regime 1, for $\beta \in \left(0, \bar{\rho}\frac{T}{\pi \delta t}\right)$, it is $\beta_{t,max}(\beta, \chi = {}^\pi/2) \lesssim {}^1/\bar{\rho}$;
regime 2, for $\beta \in \left(\bar{\rho}\frac{T}{\pi \delta t}, 1\right)$, it is $\beta_{t,max}(\beta, \chi = {}^\pi/2) \approx \frac{T}{\pi \delta t}\frac{1}{\beta}$.
Consequently it results that, in order to maximise $\beta_{t,max}$, we have to minimise $\overline{\rho}$ (to maximise the value obtained in the regime 1) and δt (to maximise the interval of β values which give rise to the regime 1). If $\delta t < \bar{\rho}\frac{T}{\pi}$ the regime 2 disappears and $\beta_{t,max}(\beta)$ keeps on the whole constant ($\beta_{t,max}(\beta) \approx {}^1/\bar{\rho}$) for nearly all the values of β then to approach 1 when β approaches 1. In figure 1 some graphs of the function $\beta_{t,max}(\beta, \chi = {}^\pi/2)$ are shown.

At present three "Salart-type" experiments [37, 39, 40] have been carried out to which a fourth one could be added [41] which had, however, the problem of $\Delta \overrightarrow{x}$ being not parallel to the direction East-West. All these experiments have not highlighted any discrepancies with the predictions of the quantum mechanics. From the experimental tests performed so far, we can therefore infer that either the model is incorrect, or, if it is correct, the value β_t must be greater that the values $\beta_{t,max}$ investigated in the various experiments (see figure 1). We can note that only in [40] Bell's inequality is really evaluated in every measurement, in [37, 39] correlations that make the violation of Bell's inequality plausible are observed and no variation of those correlations occurs during the 24 hours' measurement.

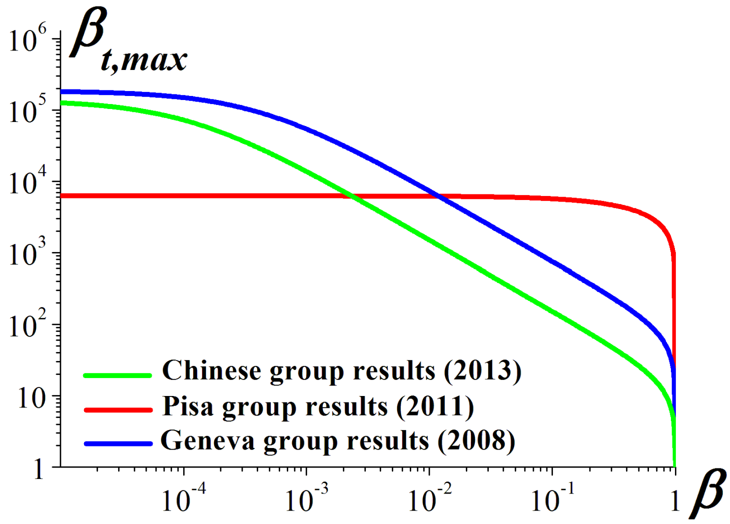

Figure 1: Graph of the function $\beta_{t,max}(\beta)$ defined in the (24) with $T = 24h$, $\chi = \frac{\pi}{2}$, $\bar{\rho}$ and δt obtained from the experimental conditions of the 3 Salart-Type experiments carried out so far. More specifically we have $\bar{\rho} = 5.4 \cdot 10^{-6}$ and $\delta t = 360s$ ($\bar{\rho}\frac{T}{\pi\delta t} \cong 4 \cdot 10^{-4}$) for the experiment of the Geneva group [37] (blue graph), $\bar{\rho} = 1.6 \cdot 10^{-4}$ and $\delta t = 4s$ ($\bar{\rho}\frac{T}{\pi\delta t} \cong 1$) for the experiment of the Pisa group [39] (red graph), $\bar{\rho} = 7.28 \cdot 10^{-6}$ and $\delta t = 1800s$ ($\bar{\rho}\frac{T}{\pi\delta t} \cong 1 \cdot 10^{-4}$) for the experiment of the Chinese group [40] (green graph).

6. Conclusions

J. S. Bell [2], P. H. Eberhard [3], D. Bohm and B. Hiley [4] agree on considering the model described above incompatible with the theory of relativity because of Lorentz non invariance of the model itself. I believe this conclusion is vitiated by an interpretation of the principle of relativity which cannot be considered correct in spite of its large diffusion. As pointed out by Galileo, the principle of relativity claims the invariance *only* for phenomena which can be reproduced below decks. Whether phenomena which cannot be reproduced below decks exist or not is a matter of competence for nature, certainly it is not a matter we can establish as matter of principle. Indeed the principle of relativity, in Galileo's form, does not claim the non existence of phenomena which cannot be reproduced below decks, it simply states that the invariance must be required only for phenomena which can be reproduced below decks. Models which hypothesize the existence of phenomena ruled by an "aether" which cannot be dragged in the lab reference frame will necessarily be non invariant; this non invariance, however, is in no way in contrast with the principle of relativity. Should possible future experiments prove the correctness of the model discussed above, important aspects of the current quantum mechanics would surely have to be modified; nevertheless nothing of the theory of relativity would have to be changed.

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