A physical distinction between a covariant and a non-covariant reduction process in relativistic quantum theories

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Abstract. Causality imposes strong restrictions on the type of operators that may be observables in relativistic quantum theories. In fact, causal violations arise when computing conditional probabilities for certain partially causally connected measurements using the standard non-covariant procedure. Here we introduce another way of computing conditional probabilities, based on an intrinsic covariant relational order of the events, which differs from the standard one when this type of measurement is included. This alternative procedure is compatible with a wider and very natural class of operators without breaking causality. If some of these measurements can be implemented in practice, as predicted by our formalism, the non-covariant, conventional approach should be abandoned. Furthermore, the description we promote here would imply a new physical effect where interference terms are suppressed as a consequence of the covariant order in the measurement process.

As has been shown by many authors [1]–[4], causality imposes strong restrictions on the type of operators that may be observables in a measurement process. These restrictions arise, as we shall see, when one considers certain particular arrangements composed of partially causally connected regions where conditional measurements take place. This type of causal connection appears when the regions of space–time where the quantum states are subject to a measurement process are partially time-like and partially space-like separated. While some operators are admissible in the relativistic domain, many others are not allowed by the standard formalism. This conclusion may be derived from two basic hypotheses, the minimally disturbing hypothesis [2] and the conventional Bloch notion of the ordering of events in the relativistic domain. The previously mentioned hypothesis assumes that the conditional probability calculus for a given set of observables related to some operators of the theory can be obtained, without introducing...
the experimental devices within the theory, with a wide range of accuracy. In other words, it is enough to consider the system decoupled from the experimental devices, with a given probability formula and a reduction postulate for the quantum state after each observable is measured on a certain space-like region. On the other hand, Bloch’s approach consists in choosing an arbitrary Lorentzian reference system and hence: ‘... the right way to predict results obtained at C is to use the time order that the three regions A, B, C have in the Lorentz frame that one happens to be using’ [5]. Although here we shall use the minimally disturbing hypothesis, we are going to use a different, covariant notion of order [6], and its corresponding reduction postulate which, as we shall see, implies different predictions in the case of non-local partial causally connected measurements, though it coincides otherwise. We show in what follows some particular cases where this physical distinction is manifest.

As has been recently advocated, the minimally disturbing hypothesis we adopt here could be avoided in the non-relativistic domain if there is decoherence in a particular basis of the device’s degrees of freedom, taking into account the trace on the environment [7]. There, the usual probability distributions are recovered and the above-mentioned hypothesis is therefore based on more physical grounds. This has attracted recent attention, with the border between the classical and the quantum world under current observation.

If one looks for an extension of this program to the relativistic domain one faces new problems. First of all, there is not a well defined relativistic quantum theory of single particles and one must extend quantum mechanics to field theories. Second, there is not a unique time order for the conditional probability calculus to be used and causal problems require further study.

Given these considerations, the most natural approach has been to maintain the minimally disturbing hypothesis and use the microcausality property of quantum field operators, that is the commutation of operators associated with space-like separated regions, to show that causality is preserved for any local measurement and, therefore, that the non-covariant order is harmless. Concerning non-local measurements, one can study to what extent this approach is physically viable and hope that in the not too distant future we will be able to better understand the relativistic extension of the measurement process. Along this line it has been shown, as we mentioned above, that certain non-local operators would not be measurable quantities. In other words, one would not be able to measure them keeping track just of the state of the quantum field system within the traditional non-covariant approach we mentioned before. Nevertheless, a final theory is still lacking and the observable character of the operators is still controversial. To our knowledge there is not a single approach that overcomes the measurement problem in quantum field theory where the causal and space–time properties of the measurement process are matched. The analogous decoherence effect has not been fully understood and it has not been shown that the non-covariant order for conditional probabilities is harmless when including the device within the theory, though it is natural to think that the microcausality property will play an essential role.

It is therefore meaningful to explore the possibility of maintaining the minimally disturbing hypothesis as a first attempt to understand the causal versus the non-local aspects of the measurement process, by extending our relational covariant approach in order to include a wider class of admissible non-local operators. We discuss the physical consequences of this extension later.

In a previous set of papers [6, 8, 9] we introduced a covariant realistic description of quantum states and the reduction process in relativistic quantum mechanics and relativistic quantum field theories, something which has been studied by many authors in different contexts [1, 5, 10]–[13]. We have shown that it is possible to extend a realistic description to the relativistic domain where
a quantum state may be considered as a relational object that characterizes the disposition of the system for producing certain events with certain probabilities among a given intrinsic set of alternatives. To understand this notion of reality better let us recall what Omnes used to ask about physical processes: ‘tell me a story’ [14]. The actors of this story are the building blocks of physics: electrons, quarks, etc. But there is a problem for these actors—there is not even a play until they act. This is what quantum mechanics has taught us—that there are not properties before measurements. So, the image of an electron crossing, for instance, a Geiger counter is just that, a picture. One can think, nevertheless, that there is some kind of reality in this play, a relational one [6, 8, 9]. The actors exist because they have the capacity of talking to the audience. Properties are the result of the interaction. In that sense, a system is given by the set of its behaviours with respect to others. An isolated system does not have properties or attributes, since all the ‘properties’ result from its interaction with other systems. It is important to note that this is a strongly objective description in the sense of D’Espagnat [10] and it does not make any reference to operations carried out by human observers. In order to extend this point of view into the relativistic domain one begins by introducing an intrinsic order for the set of alternatives on the measurement process as follows: let us denote by $A_{R, u}$ the instrument associated with a space-like region $R$ whose four-velocity is $u$. We start by introducing the following partial order: the instrument $A_{R_1, u_1}$ precedes $A_{R_2, u_2}$ if the region $R_2$ is totally contained in the forward light cone of $R_1$. Let us suppose that $A^0_{R_0, u_0}$ precedes all the others. In other words, we assume that all the detectors are inside the forward light cone coming from this initial condition. That would be the case, for instance, for the instrument that prepares the initial state $s = 0$ in the EPR(B) experiment. In this way one can introduce a strict order without any reference to a Lorentz time. Define $S^1$ as the set of instruments that are preceded only by $A^0$. Define $S^2$ as the set of instruments that are preceded only by the set $S^1$ and $A^0$. In general, define $S^i$ as the set of instruments that are preceded by the sets $S^j$ with $j < i$ and $A^0$. Notice that any pair of elements in $S^i$ is separated by space-like intervals. This procedure defines a covariant order based on the causal structure induced by the devices involved in the measurement process. The crucial observation is that all the alternatives on $S^i$ can be considered as ‘simultaneous’ for the decision process of the quantum state.

Contrary to the non-covariant approach, we shall see that an extension of this description to the case of partial causal connections allows us to include a wider class of causal operators. It is then very important to understand whether or not this intrinsic order is physically relevant.

Let us introduce the experimental arrangement shown in figure 1. Let us suppose, following Sorkin [2], that the measurement set-up is composed by two regions, $A$, $C$, and one intermixed partial causally connected measurement on region $B$, associated with values of certain Heisenberg observables. We shall denote $P^A_s$, $P^B_b$, $P^C_c$ their corresponding Heisenberg projectors, where the upper labels represent the region and the lower ones the eigenvalues of the corresponding operators.

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As one can immediately see, the initial condition has deep relevance to the construction of the covariant alternatives. In many cases the preparation of the system is central for the determination of the initial condition. As one already knows, a quantum system involves entangled objects, therefore in a complete quantum theory one has to take the whole universe as the system. There, the relational point of view is the only way to describe the evolution. In this domain, a quantum object may not have a natural beginning beyond the big bang. If one is describing a particular portion of the universe within a given time interval, then one can consider a partial initial condition given by a particular set of events that contain the forthcoming alternatives in the forward light cone. Hence, one normally falls into a sort of statistical mixture, as is the case in non-complete measurements.

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Figure 1. Sorkin’s arrangement with an intermixed partial causally connected measurement.

Let us suppose that the measurement in region $B$ admits the decomposition of the associated operator in two partial operators related with $B_1$ and $B_2$. That is, the field operator associated with region $B$ can be put as a function of two new operators related to the portions of $B$ such that $B = B_1 \cup B_2$. Let us denote the respective eigenvalues $b_1$ and $b_2$, and suppose that the total result $b$ on $B$ is extensive in the sense that $b = f(b_1, b_2)$. For instance, let us call $(O^1, O^2)$ the operators associated with the partial regions $(B_1, B_2)$ and $O$ the operator associated with $B$. Therefore, $f(O^1, O^2) = O$ is the functional relation between them. Notice that this hypothesis includes a wide class of operators since we do not make any extra assumption on this functional relation. We shall describe these partial projectors by $P_{B_1}^{b_1}$, $P_{B_2}^{b_2}$. Then, due to microcausality\(^2\),

$$
\sum_{b_1} \sum_{b_2} \delta(b - f(b_1, b_2)) P_{b_2}^{b_2} P_{b_1}^{b_1} = P_b^B.
$$

\(^2\) Here we use that $[P_{b_1}^{b_1}, P_{b_2}^{b_2}] = 0$ which implies that we can diagonalize both self-adjoint operators, $O^1$, $O^2$, in the same orthonormal basis. The vectors in this basis are thus also eigenvectors for the operator $O = f(O^1, O^2)$ with eigenvalues $b = f(b_1, b_2)$, where $b_i$ are the eigenvalues for the $O_i$ operators. The following property is a natural decomposition for the $P_b^B$ projector.

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independent sum by using the closure relation. Hence, if one uses Bloch’s notion for the ordering non-linear with respect to the portions of the region. This prevents us from ignoring that the 

\[ \mathrm{Tr}[P_c P_b^B P_a^A \rho_0 P_a^A P_b^B] = \sum_{(b_1, b_2, b'_1)} \delta(b - f(b'_1, b_2)) \delta(f(b'_1, b_2)) \]

where the sums are taken over the whole set of possible values, and we have used the cyclic property of the trace, microcausality and the projector character of \( P_b^B \).

Now, in order to study the causal implications of this expression we are going to suppose that non-selective measurements have been performed\(^4\) on \( A, B \). Hence, the probability of having \( c \), no matter the results on \( A, B \), is

\[ \mathcal{P}^B(\text{unknown } a, \text{unknown } b, c|\rho_0) = \sum_a \sum_b \mathcal{P}^B(a, b, c|\rho_0) = \sum_a \sum_{(b_1, b_2, b'_1)} \delta(f(b'_1, b_2)) \]

\[ \times \mathrm{Tr}[P_c P_b^B P_a^B P_a^A \rho_0 P_a^A P_b^B] = \sum_{b_1} \sum_{b_2} \mathrm{Tr}[P_c P_b^B P_a^B P_a^A \rho_0 P_a^A P_b^B] \]

where we have used that \( \sum_{b_2} P_{b_2}^B = 1 \) and \( \sum_a P_a^A = 1 \). Therefore, Bloch’s approach is consistent with causality in the linear case. However, one immediately notices that this is not a general feature. As can be seen from expression (3) in the non-linear case, this formula breaks relativistic causality. This is due to the fact that in general the delta function \( \delta(f(b'_1, b_2) - f(b_1, b_2)) \) imposes a constraint on the \( b_2 \) values that does not allow us to perform an independent sum by using the closure relation. Hence, if one uses Bloch’s notion for the ordering of the alternatives, one gets faster than light signals for a wide class of operators, those which are non-linear with respect to the portions of the region. This prevents us from ignoring that the \( A \) measurement has been performed. There is no violation with respect to the \( B \) observation since an observer at \( C \) may be causally informed about a measurement carried out at \( B \). However, the above analysis implies faster than light communication with respect to the \( A \) measurement since it is space-like separated from \( C \). Therefore, the requirement of causality strongly restricts the allowed observable quantities in relativistic quantum mechanics.

Let us show this in detail in the particular case of a quantum scalar field. Let us introduce the following operator for the measurement carried out on region \( B \):

\[ [P_b^B, P_c^C] = 0 \] and \( P_b^B P_a^B = \delta(b_2 - b'_2) P_b^B \).

\[ \text{Notice that the resulting values for the measurement carried out on } A, B \text{ cannot be transmitted causally to an observer in } C. \]

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\[ \mathcal{O}(t^B) = \int_B \int_B g^B(x)g^B(y)\hat{\mathcal{O}}(x,t^B)\hat{\mathcal{O}}(y,t^B) \, dx \, dy \]  

where \( g^B \) is a smooth smearing function for the field operator, with compact support such that it is non-zero in the region \( B \). We shall assume that any projection of the state is instantaneous at proper time \( t^B \) for the local Lorentz system, neglecting as usual the duration of the measurement process\(^5\).

Notice now, that the above operator has a non-local behaviour with respect to the region \( B \). It is easy to see that it also implies a non-linear behaviour for the functional relation \( f(b_1, b_2) \). In this case we will have the partial operators\(^6\):

\[ \mathcal{O}_i(t^B) = \int_{B_i} g^B(x)\hat{\mathcal{O}}(x,t^B) \quad i = 1, 2. \]  

Therefore we will get the functional relation \( f = (b_1 + b_2)^2 \) since \( O = (O^1 + O^2)^2 \). Now we can introduce it into equation (3), obtaining

\[ \mathcal{P}^B(\text{unknown } a, \text{unknown } b, c|\rho_0) = \sum_a \sum_{(b_1,b_2)} \frac{1}{2(b_2 + b_1)} \text{Tr}[P_c \rho_{b_2} P_{b_1} P_a \rho_0 P_a P_{b_1}] \]

\[ + \sum_a \sum_{(b_1,b_2)} \frac{1}{2(b_2 + b_1)} \text{Tr}[P_c P_{b_2} P_{b_1} P_a \rho_0 P_a P_{b_1}] \]

where we have used that \( \delta((b'_1)^2 - (b_1)^2) + 2(b'_1 - b_1)b_2) = (1/2(b_2 + b_1))(\delta(b'_1 - b_1) + \delta(b'_1 + b_1 + 2b_2)). \) Hence, one immediately sees that one cannot use, as in the linear case, the identity decomposition for the \( B_2 \) measurement because there is not an independent sum on \( b_2 \). Therefore, the standard Bloch approach does not allow us to measure operators such as the one defined in (5), nor its natural extension to an \( n \)-field function.

We shall show in what follows that the relational approach is covariant, and consistent with causality for the general type of operations we are considering, while the standard expression is unacceptable as we have seen. Let us consider again Sorkin’s arrangement with the relational intrinsic order (see figure 1). Let us start with \( S^0 \) and the preparation of the state in \( \rho_0 \). Hence we have \( S^1 = (A, B_1) \) and \( S^2 = (B_2, C) \). The key observation is the following. In order to introduce the relational covariant reduction process on this particular framework, our notion of partial order requires us to consider the measurement in region \( B \) as composed of different alternatives. That is, in the case where only a portion of the region where measurement takes place is causally connected, one needs to decompose the region into portions such that each part is completely inside (or outside) the forward light cone coming from the preceding ones. Hence the alternatives belonging to one set \( S' \) may be composed of several parts of different instruments. In fact, a particular device could contain parts belonging to different options. The decision process of the quantum state for producing an observable phenomenon in region \( B \) is now composed of two new sets of alternatives on \( B_1 \) and \( B_2 \). Within this new scenario it can be

\(^5\) This idealization is possible as much as the partial causal connection is preserved during a period of time much longer that the duration of the measurement process itself (decoherence timescale). That leads us to consider wide space-like regions for the \( B \) measurements in order to retain this ideal case. The physical effect that we are going to discuss here also would appear for generic partial causally connected devices, but it would need to consider space–time partial causally connected regions instead of thin almost space-like ones.

\(^6\) In [9] we have studied the spectral decomposition for these kinds of operators in the Klein–Gordon free field.

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immediately seen that the conditional probability formula for the above experiment should be calculated as

\[
P(a, b, c|\rho_0) = \sum_{(b_1, b_2)} \delta(b - f(b_1, b_2)) \text{Tr} [ P_c P_{B_2}^R P_{B_1}^R P_a^A \rho_0 P_a^A P_{B_1}^R P_{B_2}^R ]
\]

(8)

where the sum is taken over the set of partial projections compatible with the final result \(b\) on region \(B\). As we have mentioned, the individuality of the whole measurement still persists since we do not have access to any partial result \(b_1, b_2\), but only to the total result \(b\) obtained on \(B\) after observation. Nevertheless, due to the intrinsic relational order, the quantum state must decide about the measurement on region \(B\) in a ‘non-simultaneous’ set of alternatives: first the alternative \(S^1 = (A, B_1)\), followed by \(S^2 = (B_2, C)\). This implies that the quantum state may pass through a chain of partial decision processes to produce the final result \(b\) on \(B\). The resulting wavefunction collapse, associated with the registered value \(b\), should take into account this chain of partial decision processes associated with the intrinsic covariant order. This fact is therefore reflected in (8) by the sum of the partial projections. Notice that we are not considering an experimental set-up with independent measurements on \(B_1, B_2\). In fact, it is easy to see that both approaches would coincide for this last case. The measurement process we are considering here only involves the non-local measurement of \(b\) on \(B\) without further information left. Hence, we should understand the process given in (8) as a consequence of the relational intrinsic order for the case of partial causally connected non-local measurements, rather than the result of an experiment with actual independent measurements on the portions of region \(B\). This is a very important departure from the standard viewpoint because we are allowing the possibility of partial decision processes, i.e. projections, of the quantum state to produce an observable phenomenon in region \(B\) with result \(b\), but without the aid of partial local registrations. This is an inescapable consequence of the covariant order. Therefore, (8) implies a new kind of physical process where a quantum state may be projected without producing any macroscopic observable effect, but instead, as part of a chain of decision processes which ends in the final macroscopic result. As we discuss below, this effect could be consistent with a fully Schrödinger-like description of the measurement process.

It is now easy to see that this experimental setting does not lead to causal violations for non-selective measurements on the \(A, B\) regions. In order to do that, we simply perform the sum of the unknown results \(a, b\), getting

\[
P(\text{unknown } a, \text{unknown } b, c|\rho_0) = \sum_a \sum_b P(c, a, b|\rho_0) = \sum_{b_1} \text{Tr} [ P_c P_{B_1}^R \rho_0 P_{B_1}^R ]
\]

(9)

where we have used, making use of microcausality, the identity decomposition for the measurement on \(B_2\), and afterwards on \(A\). The final sum covers the complete set of possible values of \(b_1\). This leads to an interesting dependence of the final conditional probability (9) on the complete set of projections on the portion \(B_1\) causally connected with \(C\). This type of correlation does not imply any incompatibility with causality since it just informs an observer in \(C\) that the \(B\) measurement was performed. It is clear that we cannot extract from equation (9) any information about the final observed value \(b\) on region \(B\). Therefore, the relational approach is consistent with causality for a larger class of operators, while the standard Bloch computation is extremely restrictive as we have seen.

It is now clear that the relational intrinsic order implies a new effect for partial causally connected measurements in order to preserve the consistency with causality. From a physical
point of view, the intrinsic order implies the suppression of the interference terms in equation (8) with respect to (2). In other words, quantum interference cannot arise among ‘non-simultaneous’ alternatives. Notice, however, that (8) coincides with (2) for total or null causal connection.

A final remark is in order since, as we said before, we are not taking into account the detailed description of the measurement process. We have assumed the minimally disturbing hypothesis. Under this hypothesis our approach is consistent with causality in the general case without any need of introducing the device into the system. It is frequently considered that, in order to include non-local operators, the minimally disturbing hypothesis needs to be relaxed in order to describe a measurement process avoiding causality violations within Bloch’s approach [1, 3, 4]. We have shown here that we can conserve this hypothesis by instead modifying Bloch’s non-covariant order, and adopting therefore a covariant description. The natural question to ask then is, what are the physical conclusions in connection with a possible extension of the measurement process by including the device’s degrees of freedom in the relativistic case? If the minimally disturbing hypothesis is experimentally consistent we should be able to understand this suppression of interference terms by including the measurement instrument within the theory in a fully covariant quantum description. Besides decoherence associated with the whole non-local $B$ measurement which gives us the diagonal density matrix in the $b$-basis, we still need to understand why the coefficients are calculated via (8) and not (2). It is clear that this interference suppression related to the intrinsic covariant order must rely on physical grounds. First of all notice that the difference between (8) and (2) is quantitively important in the case of partial causal connection, though both approaches coincide in the case of total or null causal connection. It is therefore clear that there will be a sudden change from the point of view of the probability calculus from (2) to (8), as soon as the light cone coming from $A$ connects region $B$, in order to keep a causal behaviour. It is possible to see that this change is continuous but not smooth. It is natural to ask, to what sort of mechanism would this effect be associated if one assumes that the device’s degrees of freedom are included? A possible explanation could be the following. Let us suppose a smooth Schrödinger-like wave evolution for the combined system + apparatus, and a forward light cone propagation, during the whole measurement process. Notice, however, that the location of the region where measurement takes place is still an external parameter in the theory: that is, there is a fixed external causal structure. Then the discontinuities in the derivative of the probability could arise due to the appearance of quantum fields whose Schrödinger-like propagation would affect one of the portions of $B$, and produce the above effect as soon as the light cone coming from $A$ contacts region $B$. In this case the microcausality property would start to play an essential role and discontinuities would appear involving the commutative properties of field operators. Since microcausality is still an external property related to the fixed background it is natural to associate this sort of ‘phase transition’ with the relative change in the space–time position of the measurement devices.

Summarizing, we have introduced a description of the relativistic reduction process that gives new insight into the measurable character of non-local operators in relativistic quantum mechanics. Within our approach, the measurement of a wide class of non-local operators does not break causality, contrary to what results from the non-covariant approach. Further theoretical and experimental efforts are required to understand this kind of non-local measurement. It is clear that in order to implement this type of measurement in practice, now thinking in terms of more realistic measurement instruments, it is fundamental to avoid partial decoherence on $B_1$, $B_2$ which would suppress the interference terms in (2) leading to a causal behaviour. For the

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case we have studied above, we will need a quantum system which specifically avoids a partial projection of $O_i$ due to environmental interactions. Therefore, we need a macroscopic physical system which behaves coherently during the measurement process. The recent developments of SQUID (superconductor quantum interference devices), where macroscopic states are put in coherent superposition [15, 16], may open the possibility of experimental verification. Let us outline another possible route: the operator introduced in (5) could be associated with the two-point correlation function in a non-translationally invariant superconductor. In this system the two-point isothermal susceptibility will be given by $\chi_T(x, y) = \beta G(x, y)$, where $G(x, y) = \langle 0 | \hat{\phi}(x) \hat{\phi}(y) | 0 \rangle$ is the two-point Green function for the effective quantum field associated with the order parameter. Let us now calculate the net isothermal susceptibility as $\chi_T = \frac{\partial M}{\partial H}$, with $M$ and $H$ the magnetization and magnetic field respectively. In the case of a non-translationally invariant system, i.e. $G(x, y) \neq G(x - y)$, we will have $\chi_T = \beta \int_B \int_B dx \ dy G(x, y)$ [17]. Therefore, measuring global magnetic responses in superconductors may open the possibility of introducing this sort of non-local operator. An analogous reasoning could be made also for superfluid systems. Similar measurements for fundamental fields rather than effective quantum fields need further study.

Finally regarding the possible physical applications of this interference suppression mechanism, it is worthwhile to stress that it occurs not directly related to environmental interaction but as a consequence of a covariant order in the measurement process for the case of partial causal connection\(^7\). These features may have important consequences regarding quantum information processes. Hence, to explore the experimental viability of this type of operator is crucial to continued exploration along this path.

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\(^7\) Environmental decoherence is however expected to play an essential role during the whole measurement process.

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