MUST THE MICROCAUSALITY CONDITION BE INTERPRETED CAUSALLY? BEYOND REDUCTION AND MATTERS OF FACT

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ABSTRACT: The 'microcausality' condition in quantum field theory is typically presented and justified on the basis of general principles of physical causality. I explore in detail a number of alternative causal interpretations of this condition. I conclude that none is fully satisfactory, independent of further and controversial assumptions about the object and scope of quantum field theories. In particular the stronger causal readings require a fully reductionist and fundamentalist attitude to quantum field theory. I argue, in a deflationary spirit, for a reading of the 'microcausality' condition as merely a boundary condition, inspired by Relativity, that different possible formulations of quantum field theory must obey.

Keywords: Causality, Quantum Field Theory, Microcausality Condition.

CONTENTS

1. Introduction: The problem

In this paper I explore the physical interpretation of the principle known in Relativistic Quantum Field Theory as the 'microcausality condition' (MC). The principle establishes that operators representing physical quantities at space-time points separated by finite space-like distances must commute. In 1928 P. Jordan and W. Pauli presented -as part of a covariant formulation of Dirac's quantum electrodynamics, the theory of the interaction between electrons and electromagnetic radiation- the first manifestly Lorentz (relativistic) covariant theory for free radiation fields. The requirement of Lorentz invariance of physical laws is fundamental to any relativistic theory, and it is the principle that all mathematical relations between physical observables must be independent of any inertial frame - or inertially moving observer. A fundamental element of the theory was the result that the commutators [A(x), A(x')] of the electric (magnetic) field operators at different space points x and x' could be expressed in terms of a singular function ?(x - x') -first derivative of a four-dimensional Dirac's delta function. This function was not invariant under the Lorentz transformations if x and x' were space-like separated. For the theory to be fully relativistic the commutators must be relativistically invariant. The demand of invariance on the commutator required that for space-like intervals the delta function ? and thereby the commutators vanish. Then in 1940, in a landmark article Pauli introduced a generalization of the earlier result as an independent requirement in the proof of the connection between spin and statistics, one of the most celebrated results of Quantum Field Theory. There he formulated the new principle as follows: '*we shall expressively postulate that all physical quantities at finite distances external to the light cone are commutable.*'[1] In other words, the commutators of physical observables at space-like separated points vanish.

The value of MC in the theory became established by its key role in Pauli's derivation of the spin-statistics theorem[2] and its subsequent role in other confirmed results of QFT such as the CPT symmetry theorem (for free fields) and the expression of various scattering amplitudes -dispersion relations- (for interacting fields).[3] The importance of the latter lies in the fact that it is just the main physical quantity against which field theories are tested by experiment.

Ever since it was first formulated by Pauli with its full generality MC has been upheld and understood invariably as more than the expression of a relativistic constraint on the theory. It has been presented as the fundamental (relativistic) requirement of causality for the microlevel. Its causal content has been identified in operational terms as superluminal signalling. This was Pauli's original operationalistic interpretation after the alleged demise of (deterministic) causality in quantum mechanics.[4] In the 1950s, quantum field theory borrowed by analogy from optics general constraints of causal nature on representation of physical waves: time ordering, continuity and analiticiy of the functions representing the dispersion processes.[5] With the development of phenomenological S-matrix quantum field theory, this causal formulation was introduced in Pauli's terms as a fundamental, explicitly causal constraint on dispersion relations:

> The causality requirement in the present papers is as follows: The quantum mechanical formulation of the demand that waves do not propagate faster than the velocity of light is, as is well known, the condition that the measurement of two observable quantities should not interfere if the points of measurement are space-like to each other.[6]

More generally, the causal interpretation of the principle has been directly linked to its justification. That is, the causal interpretation has been adopted to justify the principle as a fundamental axiom of quantum field theory, where the relativistic formulation is valued as the privileged expression of the notion of causality. Thus Streater and Wightman have asserted that MC is one of the assumptions *that 'define what we mean by a field in a relativistic quantum field theory.*[7] And since quantum field theory has begun to fall under philosophical scrutiny, also philosophers of science have subscribed to the claim that *'two observables must commute at space-like separation for reasons of causality.*[8]

I believe that this position rests on a strong reductionist stance towards the descriptive power of quantum field theory. What I have in mind is a broader kind of reductionism that is both a question of facts and a question of values -and categories.[9] Different disciplines and theories may hold not just different concepts and languages for describing the facts within their respective domain, but also different methodological, conceptual -or metaphysical- and cognitive values.[10] Generalizations in biology tend to differ in form from laws of physics; simplicity is more valuable a constraint on models and explanations in physics than it is in physiology; unlike in physics, in economics predictive power is more highly regarded than descriptive accuracy and completeness; interest in more elementary constituents of matter is more common in physics than in ecology. Similarly, the criterion for what counts as -not for how to test- a causal relation is not a matter of fact but a matter of value (under this rubric I include fundamental categories and conventions). It is part of the framework of fundamental categories within which a theory may offer a picture of the world.

To believe that the formulation of relativistic quantum field theory requires a characterization of causal relations -or that such a characterization is important- is just an extension of the belief that the theory offers a more fundamental and complete theory of Nature. Thus if causal notions are in place in our explanations and descriptions of phenomena at less fundamental levels, then also a theory of quantum fields -or particles- should include a model of causation -of *micro*-causality- for its fundamental micro-entities. Insofar as the fundamental entities are believed to constitute the building blocks of Nature as we know it -and the complete representation of the former offers sufficient and firm grounds for a complete representation of the latter-, the quantum physical description of causal relations would then also guarantee the intelligibility and representability of the concrete causal relations at higher levels.

Now, to ascertain whether MC provides such a necessary or desirable causal constraint in this sense we need to turn to the question of facts. We need to determine how MC introduces the requisite causal picture of the fundamental facts. Note that MC is a negative proposition. Therefore, MC is causally true if its violation describes a substantive kind of causal relation. In this regard it is important to clarify first the role and the strength of arguments from considerations of the theory of relativity. The theory of relativity establishes that an event at a space-time point can be influenced only by events at points in its past; that is, in and on its past light-cone. But this condition alone cannot capture all the philosophical models of causation that are in place in our theoretical descriptions of the world.[11] And the representation of causal influences depends on the more specific formulation of the facts that are causally related. Indeed, the theory of relativity is only a set of general constraints which any more detailed theory of material processes must satisfy.[12] The theory of relativity introduces constraints on the formulation of other physical theories, but non-relativistic versions of these are always available. In addition, there exists a diversity of abstract philosophical models of causality that detailed theories can help formulate.[13] If we desire a conceptual framework for a rich causal structure of the world, relativity is too weak. It may be inconsistent: causal connections that we describe classically in terms of forces and motion under Newton's laws violate the terms of relativity; and the notion of rigidity allows for superluminal propagation of disturbances. It may also be irrelevant: in most theories of sociology, biology or chemistry it may be at most taken for granted but hardly ever explicitly relevant. Lastly, even within the framework of the theory of relativity, the possibility of faster-than-light causal propagation, such as tachyonic particles and processes, may be defended. Relativity, then, is at most an abstract constraint on the causal stories we tell in more specific theoretical terms. But for substantive kinds of defense of MCI have mentioned, this principle does not merely impose on quantum field theory a formal stamp of relativity. It entails more than a reformulation, a generalization, or predictive power. The question to the causal fundamentalists is then whether the violation of MC entails a more concrete and substantive story of the kind we can conceive about less fundamental processes and entities.

As I said, it is often argued that, on causal grounds, MC can be justified as a principle of no superluminal signalling. The position offers experimental promise and reassurance of support.[14] But experimental grounds for MC overshadow the conceptual grounds for its physical interpretation. The former can be neither relevant nor interesting without the latter. In principle one may choose to believe that empirical correlations call for more detailed causal explanation, as one often does in the exploration of more complex classical phenomena. More importantly, in the light of the foundational demands set by the kind of reductionism I have mentioned, one cannot replace the other.[15] A Humean regularity account of causation at the classical macroscopic levels is often deemed inadequately weak. From a foundationalist stance, the causal interpretation of MC would have to support alternatives. Even if a unified criterion of causal representations is the goal, it cannot be set by quantum field theory, and MC cannot replace alternatives. So if we are asked to find a substantive interpretation of MC, experimental results alone cannot settle the issue. But then without an unambiguous determination of what MC physically (and conceptually) involves, it remains unclear exactly what it is that experiments provide so strong evidence for. The issue was raised by Barton as he considered the more specific question as to whether it is trivial to ensure that MC, which he had presented as a causal axiom, had also any bearing on causal behavior at macroscopic distances:

> The problem is both important and topical, since the forward scattering dispersion relations, which are direct and rigorous consequences of [the MC axiom], can be tested experimentally. But no such test can be regarded as conclusive until it is known what would follow if condition [MC] were not satisfied.'[16]

The latter, more fundamental question is the subject of this paper.

In the rest of the paper I will try to explore how causal the microcausality principle is. I will argue that a substantive interpretation is not necessitated by the theory, nor is it necessitated then for the justification of the principle. I will examine critically a number of arguments to the contrary including some arguments notoriously offered to address a similar question of superluminal causality in the context of EPR and Bell-type experiments. My discussion will invite a deflationary and skeptical attitude regarding a substantive interpretation and defense of the MC principle. MC has the status of a boundary condition; it represents at most the limits of the causal structure of the world. If MC were false, much more than the limits of the fundamental causal structure of the world would be lost. For understanding and justifying MC, adequate alternatives are available. My claim is by no means conclusive. It is vulnerable to the introduction of alternative and plausible motivations of the causal interpretation. I hope that my discussion will at least show that the existing possibilities will not solve the problem. More work needs to be done to find the causal structure of the world of quantum field theory.

2. How causal is the microcausality principle? (1) The uncertainty relations

What we learn about the meaning of MC in a number of textbooks on QFT is exactly what we learned from Pauli. MC gets its physical meaning and its justification negatively, as a prohibition of the type of process which its violation would imply: the measurements at two space points with a space-like separation cannot disturb each other *causally*.[17] Note that on this interpretation, a violation of MC would entail a violation of the principle of relativistic causality, and, thus, allows for the possibility of superluminal signalling. I have called this interpretation as it stands the weak, or non-substantive, causal interpretation of MC. In virtue of this precise connection between the two postulates it is not unusual to find the former as an expression of the latter. But this does not imply by any means that the principles are identical. Their causal equivalence hinges first on a substantive interpretative assumption about the physical meaning of the commutator, namely, that the non-commutation of two physical quantities implies that their measurements can causally affect each other. A closely connected secondary assumption has to be made that the alleged causal process could be used to transmit signals when the measurements are performed at different locations, and MC would describe just such a process. That is the strong causal interpretation of MC I am exploring. Recall my discussion in section 1; the question is –in what sense does MC provide a detailed picture of causal influence?

Since the first assumption is more central to the physical meaning of MC, it will be the main focus of my discussion. To begin, the following question needs to be answered: how does the commutator of two physical quantities get its physical meaning? To say that two field measurements cannot disturb each other at a distance causally is to read a whole lot of physics -and metaphysics- into a simple mathematical relation. The field theoretic commutator must then borrow its causal interpretation from its connection with some theoretical relation that tells a specific causal story. The potential source of the interpretation -and justification- I will consider is the connection between commutation relations and uncertainly relations. Schweber asserts that the justification of MC lies in its connection to Heisenberg's uncertainty relations, presumably in Heisenberg's own disturbance interpretation: the justification of MC '*stems from the fact that in the quantum theory the lack of commutativity of two observable operators implies that these cannot be measured simultaneously with arbitrary accuracy.*'[18]

In 1926 several papers giving birth to quantum mechanics showed that conjugated variables of the physical system such as the position operator and momentum operator do not commute. In 1927 W. Heisenberg showed further that the same quantities satisfy the well-known uncertainty or indeterminacy relations that bear his name. In 1929 H.P. Robertson published a general proof showing that such relations will be satisfied by any two operators that do not commute. Heisenberg described the same result in his 1930 Chicago lectures.

Mathematically, all that Heisenberg's relations (HR) contribute is a correlation between incremental (distribution or spread) functions of the measurements of two physical quantities. Is there a strong physical interpretation of HR that can support the strong interpretation of MC? A standard statement of HR is that for two quantities A and B one cannot measure A and B simultaneously without errors whose product is at least as large as some quantity (linearly proportional to Planck's constant). We have got just measurement. Where is the causal process? Drawing upon his famous microscope argument, Heisenberg supplemented the principle with a physical explanation: a precise measurement of A will cause an impredictable and uncontrollable disturbance of B and viceversa.[19] But this cannot be just, as Bohr suggested, the result of the incompatibility between accurate measurments due to the incompatibility of classical experimental setups. What the strong interpretation of MC requires is this: on Heisenberg's intepretation of HR if two physical quantities do not commute they will satisfy a relation such that the measurement of one will interfere with the measurement of the the other; if the two physical quantities are separated by a space-like interval, the disturbance will have its effect at a distance, superluminally. On what grounds do we judge the relation causal?

And where is the description of the intervening causal process? In other words, where is the causal explanation of the alleged measurement disturbances?

In a narrow sense, the problem of causal representation is based, connectedly, both on the empirical emphasis on measurable quantities and on the assumption of representational completeness of the theory. A notorious alternative is hidden-variable theories, spearheaded by Einstein's attitude to the Copenhagen interpretation of quantum mechanics. In a broader sense, the received causal interpretation of MC must stand or fall with the unavoidability of Heisenberg's own causal interpretation of HR. But Heisenberg's interpretation is not unique. Other interpretations, such as Bohr's -based on the principle of Complementarity-, have been put forward with equal acceptance.[20] Heisenberg's interpretation is not imposed by the formalism. This has an important implication for the interpretation of MC, namely, that the causal interpretation is in no way necessitated nor suggested by the formalism, and much less selected against alternatives by the empirical grounding of MC. The causal interpretation of MC is not necessitated by its connection to HR.

Not only Heisenberg's interpretation has been held on a par with other alternative interpretations of HR, but that it has also been vigorously contested. In particular, Bohr found fault with Heisenberg's microscope argument, and H. Margenau, K. Popper, L.E. Ballentine, and more recently H. Brown and M. Redhead independently have formulated thought experiments for which Heisenberg's disturbance doctrine cannot be valid.[21] Moreover, Ballentine has argued that Heisenberg's interpretation contradicts a fundamental interpretative assumption in Robertson's proof connecting HR and commutation relations. In the proof, Ballentine claims, the error functions are construed as statistical dispersions. For Ballentine, this result is more in line with the measurement procedures and brings more consistency to his favored interpretation of quantum mechanics, the statistical interpretation. On this interpretation, HR should be understood as statistical dispersion relations (SDR): for any particular (prepared) state the product of the spreads of the distributions of different A measurements and B measurements may not be less than some lower limit.[22] Clearly, the standard deviations of the statistical distributions cannot be determined unless the errors of the individual measurements are much smaller than the statistical deviations. Note that SDR, while preserving the measurement element in the interpretation, has dropped the reference to causal processes altogether:

> [SDR] refers to statistical spreads in ensembles of measurements on similarly prepared systems. But only one quanty [either A or B] is measured on any one system, so there is no question of one measurement interferring with the other.'[23]

The difficulty is more general: If causal influence is a physical process relating physical states of the field at space-time points, its description cannot be a direct interpretation of the field quantities that occur in the formulation of MC. Assuming otherwise overlooks a fundamental distinction between quantum mechanics and quantum field theory, that in the latter fields are operators. Field representations of the state at any point require the application of the field operator to a state function associated with a physical system. But this is no fatal objection. A proviso to MC must be added requiring the reference to quantum states.

There is a further reason to believe that on Heisenberg's doctrine MC cannot be interpreted causally. My suggestion is that even if in the light of all the considerations above one persisted in the adherence to Heisenberg's interpretation, one could still deny that a violation of MC entails a violation of relativistic causality in the sense that the disturbance process can be used as a causal process to transmit signals. In general, non-statistical models of causal processes include the assumption that the process can be controlled so that it transmits a signal that preserves its structure along with its causal influence. Following Salmon[24] I take this to be the type of process which the condition of relativistic causality bridles. And this is precisely the process required to make detailed causal sense of superluminal signalling. Yet, in his non-statistical interpretation Heisenberg includes a proviso, often overlooked, that might shed a different light on the process that Heisenberg's interpretation presumes: the perturbation will be unpredictable as well as uncontrollable. If this is so, it seems implausible that the violation of MC -thus far not detected- could be interpreted as a violation of relativistic causality as a model for superluminal signalling. Heisenberg's proviso seems to forestall such possibility. A similar argument has been put forward in the case of superluminal signalling in Bell-type experiments.[25] Despite the possiblity of superluminal causal implication between space-like separated measurements, their perfect lawlike correlation does not guarantee the possibility of signalling since the stochastic nature of quantum mechanics the outcome of the measurements cannot be controlled. If signalling is a sufficient condition for the occurrence of causal connections, on the same grounds signalling cannot be employed to reveal the causal content of MC. Another argument for the impossiblity of signalling with EPR-type correlations is particularly relevant to my argument since it rests on the validity of MC.[26] The argument, due to Bell, shows that given a system of correlated particles governed by a Hamiltonian, the change in the Hamiltonian due to the manipulation of some controllable quantity b, δb, on one particle will produce a change, δA, in the expectation value of the operator A measured on the other particle such that

$$\delta A/\delta b = [A, -(1/h)B],$$

where the commutator is just an expression of MC for the operators localized and measured at a space-like distance. According to Bell, the impossiblity of signalling rests on the fact that MC is not violated. In other words, a violation of MC in this context implies the possibility of signalling, and hence a causal relation. However, Bell's argument is based on a model of the situation that contains two assumptions that in genreral do not obtain: (1) the outcome of the measurement of the localized field operator ay any pioint is not controllable, as argued previously, and (2) in general the field states at any two different points are not correlated and evolving as determined by a certain Hamiltonian. Then this basis for a no-signalling interpretation of MC lacks the generality that MC is accorded as a fundamental causal axiom.

There are three specific conditions on causality, besides the possibility of signalling, that our correlations fail to meet: time ordering, counterfactual conditions and field-locality. First, time ordering has been typically associated with causal relations, especially in empiricist analyses. The action of the cause must precede the occurrence of its effect. However in intervals on space-like hyperplanes neither simultaneity, nor time ordering are fixed for all observers, or Lorentz invariant. If Lorentz invariance is a criterion of objectivity on fundamental physical relations, the purported causal relations introduced by the violation of MC cannot be taken seriously. In discussions of superluminal causation in spacelike separated EPR correlations this kind of argument has been dismissed as irrelevant.[27] Time ordering cannot define a causal relation, nor is it necessary. The alternative involves adopting causal theories of time, that is, using causal relations to characterize time ordering. This move, however, is not without its critics.[28] Second, also counterfactual analysis has been used to argue that EPR experiments involving space-like separated measurements involve superluminal causation.[29] The indeterministic nature of quantum theory allows ruling out the possibility of common-cause explanations and allows correlations to sustain counterfactual claims that had one measurement had a certain outcome, so would have had the other. Even if, as argued, such condition established causal relations, it is not met by the HR correlations. In the context of the theoretical description of correlations between identical particles EPR experiments allow perfect correlations between the precise outcome of measurements of the state of particles. The HR relations associated with MC establish, by contrast, only a weak inequality-type correlation involving the indeterminateness in the measurement of two field quantities at different points. In that respect HR relations do not seem to sustain counterfactual claims suggesting any kind of causal implication. Third, since Maxwell and especially Einstein, field theories have been introduced as embodying a very particular model of contiguous causal influence, which, to narrow the misleading current uses of the term 'locality' I refer to as 'field-locality': changes in the field at any given point are determined only by properties of the fields infintesimally close to that point.[30] As a consequence, Bjorken and Drell point out in their classic text local field theories are "theories of fields which can be described by differential laws of wave propagation."[31] Local causality does not only involve a constant (maximum) speed, which in the case of Lorentz invariant theories is the speed of light, but also continuous propagation. To make room for an event of disturbance does not amount to explaining how the propagation of disturbance is causal, or, if it is, how it comes about. As I have indicated above, I take to be of the core of a causal connection the possibility of representing an intervening process as a collection of intermediate and independently causally connected physical states or events contiguous in real space and time at the end of which the putative causal effect at issue is brought about.[32] This is the mathematical representation missing in the description of nature offered in axiom MC. I will explore this aspect further in the next section 4, below.

More importantly, even if our HR correlations were like the ones in Bell-type experiments, they would not have to be understood causally (independently of the connection to the weak relativistic causal constraint). All that the theory provides is a correlation between two measurement uncertainties at distant points. To claim that such a correlation can be interpreted as offering the possibility of superluminal signalling completely misses the point of providing any substantive causal explanation. Correlations might test for causal relations or call for causal explanation, but they cannot simply replace them.[33] More than a Humean regularity account of causation is needed here if MC must be credited as a constraint on causal processes for the microlevel -with or without signalling involved. A similar situation can be found in the literature on Bell-type experiments, where the debates turn on the possibility of providing a satisfactory causal explanation for the EPR correlations, without a loss of richness in the notion of causality employed.[34] But, as I have argued, in the case of MC familiar features associated with causal relations appear to be absent. I will come back to correlational probabilistic models in the last section.

I have argued that a correlational analysis of causation through HR is either unavailable or too weak to flesh out the weak causal interpretation of MC. Finally, I want to claim that it is also too strong. Insofar as it points to a causal influence as a physical process, it assumes both the physical reality and unambiguous measurability -value determination- of properties described by the quantities that satisfy MC. Relativistic formulations of electromagnetism are based on four-dimensional gauge fields or potential functions as fundamental quantities. They furnish a unified, relativistic formulation of the theory, as well as a simpler unification with other theories, such as in quantum electrodynamics. One might argue that Aharanov-Bohm-type experiments suggest the physical reality of states described by electromagnetic potentials. Yet electromagnetic gauge fields are not directly and unambiguously measurable at any point.

3. How causal is MC? (2) Analogy with quantization relations

3.1. Analogy with first quantization

The commutation relations between, say, position operators or between momentum operators were introduced as heuristic rules for first quantization of general canonical variables of a dynamical system.[35] The main rule that position operators and momentum operators do not commute was associated with the facts that they are conjugated variables relative to each other, and in this sense quantum physical quantities were radically distinct from classical quantities. Since in the particular case of field theories within a Hamiltonian framework, field operators and their respective conjugated momenta act as the general canonical variables, one might draw on the rules of first quantization to dictate the commutation relations between field operators. However, the commutation relations that constrain the canonical operators as rules of quantization were never given by way of explication any additional intrinsic (primitive) physical meaning. Consequently, this connection will not do. The connection between the commutation rules for conjugate variables and indeterminacy relations is an independent one.

3.2. *Analogy with second quantization*

An alternative derivation in some texts[36] builds on the construction of field operators in terms of creation and destruction operators which satisfy, in turn, commutation rules. Yet the transfer of physical meaning from the elementary commutation relations for the creation and destruction operators will not do the job either since these operators are defined in terms of position and momentum operators for quantum harmonic oscillators. These commutation rules must ultimately be derived from the commutation rules of first quantization for position and momentum operators. But I have pointed out above that the first quantization rules do not carry any physical interpretation of their own.

4. *How causal is MC? (3) Connection between commutators and propagators*

Can propagator functions depict the causal process that the weak causal interpretation of MC constraints? I have pointed out above that for electromagnetic radiation fields, and, in general, also for free scalar fields, the commutator of two field operators at different space-time points can be expressed mathematically as a singular function of the two points. The temporal derivative of such function at the origin is a delta function, Δ, of the spatial components of the points. Like the field operators, the singular function is a solution of the homogeneous field equation. More generally, in the presence of a 'source', the mathematical function by which it is represented will constitute an inhomogeneous term in the field equation. Also in such case there exists in general a function in terms of which the commutator of two field operators can be expressed. It is the so-called 'propagator' or Green's function. (Hereafter I will primarily use the term Green's function, as it does not bear any physical connotation that might prejudice the discussion.) For expectation values of measurable quantities, the retarded Green's function in the future direction can be expressed as

$$G(x, x') = \eta(x0, x0') <0| \{A(x), A(x')\} |0>,$$

where

$$\eta(x0, x0') = 1, \text{ if } x0 > x0',$$

and

$= 0$, if $x0 < x0'$.

The Green's's function is a solution of the particular inhomogeneous field equation with a unit source, that is with a delta function as the inhomogeneous term. In section 1 I have emphasized the fact that in different presentations of MC, Pauli and others take the physical interpretation of the comutation relation for space-like intervals as primitive; that is, the physical interpretation is the basis on which they justify the mathematical formulation of MC as the vanishing of the commutators, and the result determines, in turn, that the Green's function in terms of which the commutator can be expressed will vanish as well. And not viceversa. But in previous sections I have claimed that standard independent readings of commutators cannot convincingly support the causal story that MC would tell. In this section I will explore, and dismiss, the reverse strategy. I will take the vanishing of the Green's function as the point of departure for Pauli's causal justification of MC, the vanishing of the commutator on physical grounds. The initial query about MC takes now the form of whether the non-vanishing of the Green's functions -propagators- suffices to describe the processes of non-local causation and, in the stronger reading, the processes of superluminal signalling that MC would proscribe.

Like the field operators that satisfy the field equations, a Green's function is a linear and square integrable operator defined on quantum states of the Hilbert space. Specifically, the Green's's function is the inverse of the Lagrangian operator.[37] It symbolizes the contribution to the general field operator -solution of the inhomogeneous field equation- associated with a generic unit source. In the presence of any source or any interaction term involving other fields, the Green's function appears in the component of the general field operator that symbolizes the contribution associated to the source or the interaction at a particular space-time point. This component is part of the general solution of the inhomogeneous field equation and takes the form of an integral of the Green's function times the source of the interaction term (expressed by the Lagrangian operator L int).

$$A(x)= Ao(x) + \int dx'\ G(x, x')\ \partial L\ int/\partial x'.$$

In this picture, it is clear that the bare Green's function operator is completely independent of the term representing any perturbation due to a particular physical interaction or physical source. In this sense, the Green's function operator does not depict a physical process linked to the source. Within the framework of local field theories any appeal here to pre-Einsteinian action-at-a-distance notions of causality is ruled out.

Let's go back now to the relation between the commutator and the Green's function. I want to show first that a violation of MC alone conflicts with the possibility of any causal process of superluminal signalling via measurement perturbations. Given two space-like separated points, the commutator of the field operators at the points can be expressed mathematically as a Green's function operator that can be mapped onto such points. This is all the theory says. For the justification of MC in its full generality, this connection should be helpful at least in the cases of both free fields with a source and for free fields without a source. In the first case, the Green's function is the singular function solution of the homogeneous equation; in the second, the Green's function proper. Recall, however, that neither the Green's operator nor any singular delta function can symbolize on their own the connection between a field operator at one point and the function for a physical source or a physical interaction at another. The function representing the physical perturbation that contributes to the field operator contains the source or the interaction term together with the Green's function -misleadingly associated to its propagation- but is independent from it. In other words, the origin of the perturbation must be represented by an independent element that appears in the theory as the inhomogeneous term of the field equation -and that term cannot be the same field operator solution to the homogeneous equation and acting as a source. The explication of MC includes measurement perturbations, that is, external to the field and independent of its natural fluctuations. Hence, talk about any propagation of a physical perturbation due to measurement interaction requires the explicit introduction of an interaction term in the Lagrangian operator and thereby in the field equation. But this raises two serious difficulties for the standard interpretation of MC. First, by requiring an extra term as part of the physical theory, the interpretation paradoxically entails a modification the theory it was meant to interpret. As a consequence, justifications of MC by appeal to propagators cannot do the job with full generality insofar as MC holds for free fields, that is, solutions to the field equations without interaction terms. Second, recall that in the presence of any interaction terms, the direct relation between the two-point Green's function and the commutator of the two field operators in MC simply does not hold. In conclusion, any justification of the causal interpretation of MC as a principle of no superluminal signalling based on the connection between MC and the Green's function -or propagator- is either insufficient or selfcontradicting. The causal interpretation of MC as a principle of no superluminal signalling by measurement perturbation cannot be borrowed from a physical interpretation of the Green's function for any measurement situation.

Even if these consistency obstacles could be successfully circumvented, the violation of MC expressed in terms of the Green's function will not suffice to guarantee the possibility of superluminal signalling. In fact it is not clear that such violation could be easily detected. For at least four special conditions would have to be satisfied by the operator that represents the measurement interaction in the field equation. Consider the following measurement situation: The value of a property represented by a certain field operator F is measured by two experimenters, A and B, at two different space-time points, x and y, separated by a space-like interval. The Green's function connects the operator M representing the contribution to F of the measurement interaction at the location of the measurement, say x, and the field operator at different points, say y. Note that since the field equation is about field operators, and not field values, and similarly that the Green's function establishes a mathematical relation exclusively between operators, the perturbation and thereby the correlation will be independent of the value of the precise outcome of the measurement of F at y, since only the perturbation is, metaphorically speaking, "transmitted". But as pointed out by analogy with discussions of EPR correlations, due to their stochastic nature quantum states only assign probabilities to measurement outcomes and their controllability is not generally guaranteed.

For any quantum state on which the field operator is defined, necessary to determine the physical value -not just the form of the operator- of the field quantity, the empirical result is the expectation value of the field operator. But considerations of precise field values are of the greatest importance here because in order to make an accurate assessment of the magnitude of the measurement perturbation we need previous knowledge of the precise theoretical value of the field in the absence of such perturbation. Yet, at this point we must face a mathematical obstacle rooted in the very basis of the quantum formalism: unlike classical observable functions, quantum observables cannot in general be said to have absolutely exact theoretical values; continuous quantities, such as position or field strength, are represented by operators which have no eigenvectors in the Hilbert space with eigenvalues in the continuous part of their spectrum.[38] A further constraint, on the measurement operator, is that its value must be unique, known, and constant, so that it can be ideally detected throughout a series of different runs of the experiment. Yet, nothing in the theory, much less in the practice, guarantees that even these conditions obtain altogether. Even if these conditions obtained it cannot be guaranteed that they are sufficient conditions for the signalling to be successful. By contrast, in Bell-type experiments a hypothetical violation of the condition of parameter independence (ot Jarrett-locality) sets a much more plausible scenario for the conceptual and practical possibility of superluminal signalling, due partly to its formulation in terms of qualitative rather than quantitative measurement parameters involved in the correlation, partly to the finite and discrete spectrum of possible -and correlated- outcomes.

Causality has to do with causal processes and causal mediators. Causal processes are spatio-temporally continuous collections of physical states or events in space and time. The mediating intermediates between the relevant cause and effect are themselves sufficient causes in such a way that intermediate stages make earlier stages causally irrelevant. (In probabilistic models of causality the latter condition is guaranteed by the Markov condition: at different times probabilities for events must factorize, and causal mediators upon which the probabilities of effects are conditionalized must screen off each other.) A more stringent requirement, harder to accommodate with full generality, is the capacity of the process to transmit a mark,[39] which is a sufficient condition for signalling. If there is any hope for the genuinely causal interpretation of MC borrowed from an analysis of propagators, the Green's functions must depict causal processes as collections of physical events or states in real space-time. By physical states I understand the value of a property in space and time. But the Green's function clearly does not represent such type of events. Recall that the Green's function helps represent the contribution of a source or interaction operator at one space-time point to the field operator at another point. And the field operator itself does not represent a value of a property, but rather a catalogue of values of the property to be picked out by the particular quantum state. Moreover, the Green's function relates by definition the field operator at a certain space-time point exclusively to the particular location of the source that contributes to the field. So it leaves out of the picture any type of intermediate state and in general cannot be factorized into different parts of the hypothetical "process". MC alone can establish neither the contiguity nor the causal nature of the alleged propagation.

In an alternative picture, Green's function can be analysed as part of a Feynman decomposition of a scattering amplitude in the absence of interaction. For free fields, Green's function for two points can be represented as a propagation line between two sources in a Feynman diagram. Mathematically, it corresponds to the amplitude between an initial and a final vacuum state of the time-ordered product of the field operators at each space-time point. The field operator can be decomposed into a positive and a negative frequency part which in turn can be associated with a creation and a destruction operator, respectively. In the case of fermionic fields, such as Dirac's field for the electron, the amplitude involves a particle as well as an antiparticle. For a fixed temporal ordering of the events t(x)>t(y), the Green's function between two points can be expressed as the amplitude <0| F(x+) F(y-)|0>, where F(+) and F(-) represent the positive and negative frequency parts of the free field operator, corresponding to a destruction and a creation operator respectively. The standard physical interpretation of such Green's function is that it represents the probability amplitude for creating a particle at y at time t(y), and destroying it at x, at time t(x)>t(y).[40] In general, the two point Green's function can be interpreted "in terms of the creation, propagation, and destruction, of our particle between two points."[41]

But we do not obtain a more concrete causal picture when we take Green's function as part of a Feynamn diagram, where all causal asymmetry has been reduced to the temporal ordering of events reportedly depicted. This interpretation of Green's function is misguided on two counts. First of all, no term in the amplitude can be said to literally and directly describe the propagation. It can be argued that in general no elements in terms of a series expansion corresponding to Feynman diagrams can be taken realistically.[42] Second, the informativeness of the theory does not require ontological commitments regarding the creation and destruction operators as really describing physical creation and destruction of particles. It may be argued, as Teller has done, that creation (raising) and destruction (lowering) operators are merely mathematical tools that facilitate the formal treatment of the state of the quantum field in terms of a system of states of quantized, coupled, superimposable, harmonic oscillators:

> But nowhere does application of creation and annihilation operators give one reason to think that they describe actual creation and annihilation events (...) The state itself is simply a great superposition formed from elements in the catalogue [of possible values], a superposition which at each time gives us the probabilities for

> observing this or that combination of "particle" events. Between observations we only have shifts in the amplitudes for the elements catalogued by the creation and annihilation operators (...) The theory tells us nothing about how such phenomena materialize out of the current superposition when we make a measurement.[43]

In addition, Teller has drawn attention to the fact that in relativistic theories the position variable does not correspond to a position operator as it does in the familiar non-relativistic Schrödinger theory. Hence, Teller concludes,

> even if, in general, we are warranted in thinking of raising and lowering operators as describing the creation and annihilation of quanta, the operators represented by Feynman diagrams would still not represent creation and annihilation at precise space-time points.[44]

The considerations presented suggest a negative conclusion. In the light of the completeness of quantum field theory, Green's functions do not properly represent any actual process of causal propagation. On no interesting view of causation can the connection between commutators and Green's functions provide sufficient grounds for the causal justification and interpretation of MC; neither for the weaker reading of MC as a principle of local causality, nor, much less, for the stronger one, as a principle of no superluminal signalling that would flesh out substantially and more specifically the weaker, relativistic causal constraint. More generally, MC does not seem to necessitate nor admit of any additional strong causal justification in any manner that is both natural and sufficient.

5. Non-causal justification of MC

Thus far I have been trying to associate MC to a detailed causal representations of physical processes that flesh out the weak causal content that MC incorporates from the theory of relativity. But natural and substantial causal interpretations of the theoretical descriptions available seem elusive. That does not eliminate any causal understanding of MC. As I said in section 1, I believe that in that sense MC can only have that status of a boundary condition; it only sets a general (relativistic) constraint on the causal structure of the world. The connection I have discussed might provide the required basis. But the representation of such structure must be found elsewhere.

I have also said that a richer causal representation was motivated from a narrow fundamentalist and reductionist attitude about both physical fact and values. From that perspective, quantum field theory must include not only the representation of the fundamental entities and processes that somehow make up the world, but also the requisite representation of causal relations between them. That stance allegedly justifies MC. Yet, such a stance assumes that causal representations must not only be shared but also can be fixed in a unique manner and must be instantiated at the most fundamental level of composition. It also assumes that causality at fundamental levels of description is sufficient to guarantee and make sense of causality at less fundamental levels, and that the latter depend on the former. But both assumptions are unreasonably stringent.[45] I believe they are implicit in the weak causal interpretation of MC as imposing on quantum field theory the stamp relativity.

The justification of MC does not depend on a causal interpretation. I want to call attention to additional sources of justification that secure the place of MC in quantum field theory. I think the door is not yet closed, for instance, to justifications from general principles that would flesh out MC with some physical meaning or philosophical relevance. Consider Jordan and Pauli's result that the vanishing of the commutators can be derived from the requirement of Lorentz invariance on the delta function.[46] The result can be extended to the Green's functions in general insofar as, due to the integration conditions we choose in accordance with our physical intuitions, their mathematical expressions typically contain factors with the form of step functions that fix some temporal ordering of events - we talk about retarded and advanced Green's functions/propagators, or combinations of both. In relativistic quantum field theory, the requirement of Lorentz invariance is meant to enforce the desideratum that all mathematical relations involving observable quantities be independent of the reference frame of all possible inertial reference frames. But the commutation of two field operators at different space-time points cannot be Lorentz invariant if the Green's or delta function with the stipulated time ordering does not vanish for space-like intervals. MC gets its meaning exactly from this contribution to the fundamental symmetry (invariance) of the theory.

But we need not look for a causal story behind this justification. It is not an uncontroversial assertion that the postulate of relativistic causality can be justified by the requirement of Lorentz invariance or, for that matter, that it is necessitated by other first postulates of relativity,[47] contrary to what Pauli and others assumed when justifying MC. Yet if some principle of causality must be imposed together with Lorentz invariance to add up to a requirement of relativistic causality, it is not obvious how exactly this requirement would be encapsulated by or should be unambiguously read off the boundary constraint on the singular functions. In addition, seeing causality in the preservation of mere physical time-ordering is too loose a way of thinking about causality altogether. We need to ask what it adds to the physical picture.

The derivation of MC from consideration of Lorentz invariance applies exclusively to free fields. Nonetheless, even though it cannot be extended, the justification deserves more credit. The commutation rule of MC can in fact be derived from the requirement of Lorentz invariance also for the case of fields in interaction.[48] In developing a relativistic theory of fields with any spin Weinberg applies the perturbation calculations to the S-matrix amplitude, which can be expressed as a function of a time-ordered product of Hamiltonian operators. For the S-matrix to be Lorentz (relativistic) invariant Weinberg requires that the Hamiltonian density function H(x) that corresponds to the interaction be a scalar and that two such functions taken at different space-time points on a space-like interval must commute. Now, the validity of the second condition is guaranteed precisely by the commutation (anticommutation) of the fields contained in H(x) (provided that H(x) contains an even number of fermions).

The demand of Lorentz invariance, consequently, seems to sufficiently justify the MC condition for field operators without raising the issue of causal connections. In point of fact, if the commutators expressed a general constraint on causal processes within relativistic theories, it would be hard to reconcile the relativistic character of a theory with one of its results, e.g., that certain physical observables fail to commute. For it can shown, in particular, that for relativistic free scalar fields,

> the commutator of the local density [number of particles] N(x,t) with that another spatial point but at the same time [e.g., N(x',t)] goes to zero only if the two points are separated by a distance |x - x'| >> (1/m) [Compton wavelength of the field particle].[49]

If no conflict arises for Henley and Thirring, it is only because they see in the commutator only a non-causal issue of definiteness of values for the number operator.

The derivation from Lorentz invariance is a formal deductive justification from general theoretical constraints, from the top-down. Experimental, bottom-up, inductive support for MC is also available. It is, just like HR in section 2, connected to statistical considerations of measurement outcomes. The argument is due to Lüders and derives MC simply as a requirement of statistical independence between the outcome of experiments. The expectation value in a pure state of an operator at a space-time region is compared with the expectation value in a mixture of eigenstates of another operator, measured at another space-time region. The two only agree if both operators commute.[50] However, the argument assumes that conditional probabilities in quantum mechanics can be computed using the so-called "Lüders rule". Hence the applicability of this derivation of MC is restricted to idealized, non-disturbing measurements. The derivation is consistent with the weak causal relativistic interpretation of MC, but it does not require, nor does it warrant, any stronger causal description or more general metaphysical principle. As in the less clear case of HR, justifying the statistical independence on causal grounds requires a deeper causal story that the theory, even if complete, could not tell. To identify the statistical dependence with causation *simpliciter* amounts to a weak empiricist account -perhaps a Humean regularity account- of causation. If this move has any payoff, methodological, cognitive or other, it cannot be taken for granted and needs motivation. Finally, we should not forget that MC has a certain degree of support from all the empirically established results it contributes to, such as the spin-statistics theorem and the CPT conservation theorem. The first associates statistical behavior with spin value; systems with even spin values, or bosons, and with odd spin values, or fermions, obey different commutation relations and statistics. The second theorem asserts the invariance of the dynamics of an interaction under the product of charge-reversal, time-reversal and parity transformations.

6. Conclusion

I have claimed that the principle of microcausality in quantum field theory has been interpreted on the basis of a justification as a fundamental causal principle within the theory. I have argued that such an interpretation can be linked to a narrow reductionism about values and not just facts at the allegedly fundamental micro-levels of description. And I have defended that neither a strong causal justification, nor the interpretation that follows from that stance is required by the theory itself. In causal terms the principle of microcausality may be understood as a negative boundary condition, namely the specific application to quantum field theory of a general relativistic constraint. But it does not capture all that there might be to the causal structure of the world of quantum fields. This does not mean that looking for such a structure is fruitless or inconceivable. However, that project cannot be reduced to a causal interpretation of the principle. I believe that the value and feasibility of the project can only be taken for granted on reductionist considerations regarding the "fundamental" character of the entities and processes that quantum field theory describes. In fact, it is possible not to take any prior philosophical interest in causality for granted and yet be able to appreciate all the interest and merit of quantum field theory. In this sense I have argued that the emphasis on a causal interpretation is not the only insightful way to justify the place and to understand the function of the microcausality principle in the theory. I hope this conclusion proves insightful enough.

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Notes

1 Pauli (1940, p. 716).

2 Pauli (1940). See also notes 4 and 5, below.

3 See Weinberg (1964).

4 Pauli (1940). By commutator he understood in general both the commutator $[A,B]_- = AB - BA$, and the anticommutator $[A, B]_+ = AB + BA$ -satisfied by particles ruled by the exclusion principle; see the presentation of the same postulate in Belinfante and Pauli 1940. From the postulate Pauli derived the the Bose-Einstein statistics for free particles with arbitrary integral spin. In order to establish the connection between spin and statistics, Pauli introduced two physical postulates on any quantized field theory: 1) the commutator of two physical observables pertaining to space-time points separated by a space-like distance must vanish; and 2) there is no infinite number of states of negative energy. The quantization of integral spin theories according to Jordan-Wigner anti-commutation rules (leading to Fermi-Dirac statistics) violates the first postulate, whereas the quantization of half-integral spin theories according to Bose commutation rules (leading to Bose-Einstein statistics) violates the second Now, for Pauli this postulate carried a momentous and direct physical meaning; it expressed "*the fact that the measurements at two space-time points with a space-like distance cannot disturb each other,* since *no signals can be transmitted with velocities greater than that of light.*" (my italics) The operationalist formulation stands in accordance with the Copenhagen spirit. Pauli associated the case in which the commutator does not vanish with the availability of a causal process of superluminal signalling in which the controlled measurements of two physical quantities interfere with each other. But for Pauli such process would flatly contradict the spirit of the relativistic framework -which he wanted his field theory to incorporate- in the form of the principle of relativistic causality or first signal. In 1941 Pauli published his article 'Relativistic

Field Theories of Elementary Particles', the work he had presented at the Solvay conference of 1939 and that would set out the fundamentals of Relativistic Quantum Field Theory. The causality condition appears again as a fundamental postulate. For reasons that will be of importance later, it is worth noting here that in both articles the causality condition enters the theory with a primitive or axiomatic status. That is, unlike in the 1928 article, from the null commutators postulate (MC) dictated by the condition of relativistic causality Pauli derived the null boundary conditions at space-like separated points for the functions in which the commutators of the fields can be expressed, *and not viceversa.* See Belinfante and Pauli (1940); and Pauli (1940, 1941).

[5] Gell-Mann, Goldberger, Thirring (1954), Godlberg (1955) and Toll (1956).

[6] Gell-Mann, Goldberger, Thirring (1954, p. 1612).

[7] Streater, Wightman (1964, p. 100); see also Haag, Kastler (1964), and Streater (1988).

[8] Redhead (1989, p. 15).

[9] C. Elgin has offered a specific discussion of this kind of reductionism in the context of the mind-body problem, in particular regarding the question of what counts as a lawlike generalization; see Elgin (1997, ch.2). See also Dupré (1993).

[10] This does not mean that there exists agreement within each discipline. See Cat (1998).

[11] Many other philosophical notions do not depend on the theory of relativity, which leaves ample room for reservation as well as, diversity and disagreement. See, for instance, Stein (1968, p. 16, n. 16).

[12] Teller (1989, p. 212).

[13] For a recent survey see, for instance, Hausman (1998).

[14] Especially in the wake of Bell's theorem and its experimental tests.

[15] This reasoning applies also to the interpretation of Bell-type correlations.

[16] Barton (1963, p. 12).

[17] See also Itzykson and Zuber (1980, p. 118).

[18] Schweber (1961, p. 223); see also Heitler (1939).

[19] Heisenberg (1927, 1958).

[20] See Jammer (1966).

[21] Margenau (1963); Popper (1967); Ballentine (1970); Brown, Redhead (1981).

[22] Ballentine (1970).

[23] Ibid.

[24] Salmon (1984).

[25] See Maudlin (1994, p. 82-7).

[26] Bell (1987, p. 60-1) and Maudlin (1994, p. 85-6).

[27] Maudlin (1994, p. 154-6).

[28] See Nerlich (1982).

[29] Maudlin (1994, p. 130-8). Counterfactuals, according to Maudlin, constitute a weak condition that implies causal implication, but cannot establish a causal direction or eliminate common causes.

[30] See Einstein (1931), Ben-Menahem (1993) and Bjorken, Drell (1965).

[31] Bjorken, Drell (1965, vol. 2, p. 4). See also Einstein (1931).

[32] Salmon (1984).

[33] Cartwright (1989, 1999), and Hausman (1998).

[34] See for instance essays by van Fraassen and Fine in Cushing, McMullin (1989), and Healey (1992).

[35] Dirac (1925).

[36] See, for example, Henley, Thirring (1962).

[37] See Barut (1980, p. 150).

[38] See Teller (1979).

[39] Salmon (1984).

[40] Ryder (1984, p. 198).

[41] Ibid., p. 200. In more complex processes involving scattering interactions the propagator is said to represent the propagation of a virtual particle.

[42] See J.R. Brown (1991).

[43] Teller (1991, p. 18).

[44] Teller (1995).

[45] Dupré (1993) and Glennan (1996, 1997). Glennan argues that deterministic mechanisms can produce stochastic behavior and stochastic mechanisms can produce deterministic behavior.

[46] Jordan, Pauli (1928); see Barton (1963) and Schweber (1961) for free scalar fields; for free electromagnetic fields, see Dirac's lectures on quantum field theory.

[47] See Friedman (1983).

[48] Weinberg (1964).

[49] Henley, Thirring (1962, p. 45).

[50] See Lüders (1951); a reconstruction is offered in Malament (1995).

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