NON-LOCALITY AND THEORIES OF CAUSATION *

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Abstract. The aim of the paper is to investigate the characterization of an unambiguous notion of causation linking single space-like separated events in EPR-Bell frameworks. This issue is investigated in ordinary quantum mechanics, with some hints to no collapse formulations of the theory such as Bohmian mechanics.

1. Introduction

In the natural as well as in the social or psychological domain, puzzling phenomena call for an explanation, and there is little doubt that the connection among quantum events across spacetime—known as *non-locality*—is indeed puzzling. Events that we might reasonably consider mutually independent, according to our best theory of space and time, turn out to influence each other. But as soon as we try to understand what this 'influence' could amount to, we find ourselves in deep physical and philosophical troubles, and if we attempt to investigate the connection between non-locality and causation, the situation may become even more complicated. For if for the sake of the argument we assume we have a vague intuition of what non-locality might be, several are the questions worth asking. Is a *causal* view of non-locality itself possible? In particular, can the nature of quantum non-locality be somehow clarified by viewing it as grounded in some (perhaps unfamiliar) sort of causation? Which properties should this sort of causation satisfy?

There are two preliminary and general circumstances that need to be taken into account but that, at the same time, contribute to make the picture unclear. First, there seem to be different ways in which non-locality is manifested in quantum mechanics. Second, the notion of causation itself is far from being understood in an univocal and uncontroversial sense. The intuition according to which the occurrence of a physical event A determines (produces, brings about, raises the probability of, ...) the occurrence of a distinct physical event B—in which case A is said to be the 'cause' of B—can be represented differently in

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different causal theories. Within the physicists' community, for instance, it is assumed—tacitly or not—that events recognized to be causes must be temporally prior to their alleged effects, and the causal doctrine based on this assumption is sometimes referred to as 'relativistic causality'. This terminology is itself biased, however, since it takes for granted that special relativity provides the strongest possible support for this assumption. In fact, a rich philosophical debate has shown that if, more generally, the only requirement to be satisfied is the impossibility of generating causal paradoxes, several causal theories may be developed without assuming any temporal priority of causes. Moreover, different causal theories may have a differing degree of adequacy when applied to the domain of microphysics. The evaluations that may be made of their basic causal principles according to different formulations and applications of the principles themselves may widely differ, so that when one claims to defend or counteract a causal view of non-locality, he should specify in advance what is the causal theory in terms of which that view is supposed to be "causal". A clear demonstration of the interpretation-dependent character of causal notions is the debate on Reichenbach's common cause principle, according to which when two events A and B are correlated, either there is a direct connection between A and B producing the correlation or there is a different event C which causes the correlation. On the basis of different intuitions and formal definitions, opposite conclusions have been drawn on whether explanations of nonlocal quantum correlations in terms of probabilistic common causes are an option or not. This circumstance strongly supports in my opinion the view expressed in [8], according to which what is usually called the common cause principle "is not really a principle but a schema of principles that calls for interpretation" (p. 53).[1]

The pluralism of formulations that both the notion of (non-)locality and the notion of causation may assume in different theoretical frameworks can be considered primarily as a *logical* problem. In the assessment of the status and significance of a causal view of non-locality, however, we have first to take into account its *physical* background, namely we have to take into account the investigations on the physical meaning of non-locality in quantum mechanics. The standard framework is that of EPR-Bell correlation experiments, involving a two spin-$1/2$ particles' system $S_1 + S_2$ prepared in the singlet state, and such that the spin measurements are performed when the two subsystems S_1 and S_2 occupy two space-like separated spacetime regions R_1 and R_2, respectively, after leaving the source. The common feature of these investigations is basically an assumption of incompleteness for the purely quantum description of physical states; on the basis of such assumption a 'finer' state description is postulated via the introduction of extra ('hidden') variables that 'add up' to the quantum state. In this vein the first step was to introduce *deterministic* hidden variable models, in which the source state λ is postulated to be complete and assumed to determine with certainty the outcome of any measurement that can be performed on the two distant subsystems. Later the condition of determinism for hidden variables has been relaxed. Stochastic hidden variable models were then introduced, in which the state description λ allowed by the model enables one to determine not the measurement outcome but only its probability of occurrence.

Both in the deterministic and stochastic frameworks, a locality condition is usually motivated by a prescription of 'lack of influence' between the spacetime regions in which

[1] For a recent and general assessment of the issue, in addition to [8], cf. the chapter 3 of [28].

the measurement events are localized, although the specific condition of locality that was assumed in deterministic hidden variables models had to be reformulated in order to comply with the stochastic character of the more general model. The locality condition was then formulated as an independence constraint on the statistical predictions generated by the complete descriptions of the single particles' states (when the particles themselves are spatially well separated). Namely, the assumption of the mutual independence between the relevant spin measurement events was formulated as the invariance of the probabilities prescribed by λ for any outcome in one wing of the experiment under the change of some relevant parameter in the distant wing. Consequently, several discussions focused on what different locality conditions obtained when such parameter was taken to represent different things, typically parameters pertaining either to apparatus settings or to outcomes of the measurements. It is worth emphasizing that I refer here to hidden variables *models*, and not to hidden variables *theories*, for a simple reason. In the history of the hidden variables' issue, the 'theories' in which more and more general locality conditions were assumed—and whose predictions have been shown to be inconsistent with those of quantum mechanics—were in fact theories only as a *façon de parler*; whereas the only full-fledged formal construction deserving the title of theory, namely Bohmian mechanics, is explicitly nonlocal.[2]

The greater generality of these stochastic hidden variables models should make the conclusions drawn from them stronger. If locality is violated in these models, the existence of non-local influences is strongly supported, and thus their significance for the notion of causation can be investigated. However, even this more general framework provides no clear answer to the following central questions:

a) How should the causal meaning of non-locality be assessed by the point of view of the *spacetime structure* in which non-local correlations display themselves?

b) Provided we adopt the most natural interpretation of probability in physics, namely the relative frequency interpretation, and we do not turn to highly controversial notions such as chances, propensities or dispositions, what might non-local correlations tell us about *single* events confined in bounded spacetime regions?[3]

This is why in the sequel, when I will discuss the status and significance of causal relations within the issue of non-locality in quantum mechanics, I will assume as a working hypothesis that causal relations may be analyzed as holding among single events in spacetime, on the basis of processes that need not refer to any recurrence in order to be considered 'causal'. As every philosopher of causation will immediately acknowledge, this assumption is somehow reminiscent of a *singularist* approach to causation, endorsed among others by such eminent philosophers as C. J. Ducasse and G. E. M. Anscombe. In the singularist view of causation

[2] A recent detailed analysis of these and related issues is in [5] and [6].

[3] In [13] Dickson has questioned the adequacy of locality conditions based on probabilistic independence when Bohmian mechanics is taken into account, and he argued that Bohmian mechanics may be shown to satisfy or violate that kind of locality depending on how a specific model of the theory is constructed. This indicates, according to Dickson, that probabilistic independence is not adequate to capture the meaning of locality. It is worth recalling that the Dickson argument concerning the status of locality as probabilistic independence in Bohmian mechanics has been challenged in [26].

> the cause of a particular event [is defined] in terms of but a single occurrence of it, and thus in no way involves the supposition that it, or one like it, ever has occurred before or ever will again. The supposition of recurrence is thus wholly irrelevant to the meaning of cause; that supposition is relevant only to the meaning of law. And recurrence becomes related at all to causation only when a law is considered which happens to be a generalization of facts themselves individually causal to begin with. [...] The causal relation is essentially a relation between concrete individual events; and it is only so far as these events exhibit likeness to others, and can therefore be grouped with them into kinds, that it is possible to pass from individual causal facts to causal laws. [15, pp. 129–130]

I wish to stress, however, that I am not embracing a preliminary philosophical position on causation, namely singularism, and then turning to argue that causation in quantum mechanics can only make sense if interpreted in singularist terms. As I will discuss more in detail later, non-locality in quantum mechanics involves a fundamental reference to counterfactual situations, and since non-trivial counterfactuals are usually supposed to be grounded in laws supporting them, an orthodox singularist might be already suspicious. The meaning I attach to singularism is rather general and so is the motivation for adopting such a viewpoint. If for the sake of my investigation I admit the *a priori* possibility of discovering a totally new form of causation, that might explain the 'action at-a-distance' allegedly entailed by non-locality (I briefly review the modalities of such 'action' in Section 2), I still conceive it to involve physical processes connecting single events. That is, I incline to interpret this hypothetical causation as a sort of singular phenomenon, that is enhanced by the actualization of a property instantiated by a physical event and that affects the actualization of different properties pertaining distant events. The causal action displayed by this phenomenon should thus be understood as *taking place* in spacetime in some well-specified sense, although clearly not as a process propagating *continuously* in spacetime [7]. So the question is: how and to what extent can this unfamiliar causation be interpreted consistently with the more familiar spacetime structure in which—according to our well-established physical theories— single physical events live?

Within ordinary quantum mechanics—namely quantum mechanics with state reduction—a reasonable starting point for addressing the problem is in my opinion is to consider the implications of this singularist view on non-locality and causation when the state reduction is taken into due account. In the usual interpretation of quantum mechanics, state reduction is not only included among the basic postulates of the theory but is also assumed to be a real physical process. In this interpretation, it is state reduction that is supposed to actualize most properties of quantum systems, and this is a very general motivation for pursuing an analysis of the conceptual link between causation and state reduction. But there is also a more specific motivation for the study of such link. The events that might be causally connected are assumed to be located at *space-like* separated regions: thus if we take seriously—as we should—the spacetime geometry that underlies this assumption (something that Maudlin calls the *relativistic constraint*: see [25, pp. 290–292]), then we also have to take into account at least some ways out of the problem of the non-covariance of the state reduction process in *relativistic* quantum mechanics. In particular, in view of this problem, Section 3 is devoted to the exploration of some of the implications that different assumptions on *where* the state reduction occurs may have on the link causation-reduction.[4]

In following this line of analysis I do not assume, however, that a causal view of non-locality cannot be evaluated in a quantum theory *without* state reduction. Although for obvious reasons I will not take into account all no-collapse interpretations of quantum mechanics, in Section 4 I will consider what might be the place occupied by causation in standard Bohmian mechanics. Finally, some tentative conclusions on the prospects of a causal view of non-locality are summarised.

2. Non-locality, superluminal dependence and causation

Having reasons to believe that, given two events A and B, their occurrences depend on (or influence or affect) one another, is not sufficient in general to claim that A and B are causally connected. On the other hand, a mutual dependence between A and B is a good reason for us to search whether such dependence is grounded in some underlying causal mechanism, so far unknown to us. In the context of the EPR-Bell correlations in quantum mechanics, the events under consideration are assumed to be space-like separated, so that the search for causation in this context is a search for a *superluminal* causation, pursued under the assumption that our quantum-mechanical events display at least a superluminal dependence.

In order then to investigate whether long distance correlations in EPR-Bell experiments deserve to be called causal, it is convenient to briefly review the reason why in ordinary quantum mechanics such correlations can be in fact regarded as an instance of superluminal dependence between events that in a purely relativistic perspective should be taken to be mutually independent. For the sake of simplicity, I will assume here that performing a *measurement* and detecting an *outcome* are not distinct events: the terms of the hypothetical causal connection that I wish to investigate are then to be meant as *measurement-and-outcome* events.

In a standard EPR-Bell correlation experiment involving a two spin-$1/2$ particles' system $S_1 + S_2$ prepared in the singlet state, we know that the spin measurements are supposed to be performed when S_1 and S_2 occupy two space-like separated spacetime regions R_1 and R_2, respectively. Under the hypothesis that quantum predictions are correct, S_1 and S_2 exhibit a perfect spin correlation, namely if the outcome of an actual measurement of the spin up along any direction x for the particle S_1 is $+1$, the probability of obtaining -1 as outcome of the measurement of the spin up along the direction x for the particle S_2 equals 1. Hence, we may say that had the measurement of the spin up along any direction x for the particle S_1 come out -1, we would have obtained with certainty $+1$ for S_2. However, in ordinary quantum mechanics the measurement process is stochastic, namely from identical preparations we may obtain different outcomes: the spin of S_1 can be either $+1$ or -1 in different runs also when the whole set of events causally relevant to obtaining $+1$ or -1, localized in the backward light cone of the that event, is exactly

[4] For the sake of the present discussion, I assume such notions as property or emergence as uncontroversial. Of course they are not, but in my opinion it is anyway doubtful that a purely philosophical analysis of such notions could substantially contribute to a better understanding of the main issues in the foundations of quantum mechanics.

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