Chapter 8
On Time Order and Causal Order in the EPR Experiment

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Abstract The aim of this paper is to discuss the rejection of the so-called *Measurement Independence*—i.e. *No-conspiracy*—condition, in the context of causal explanations of EPR correlations, and survey some of its implications. In particular, I pay attention here to a specific way *Measurement Independence* is violated. It has to do with two assumptions about the presupposed causal order and space-time arrangement of the events involved in the EPR picture. The consequences are mostly, and more importantly, related to locality issues.

8.1 Introduction

Ever since Bas van Fraassen's influential "Charybdis of Realism ..." (van Fraassen 1982) it is a widespread opinion among philosophers of science that common cause accounts of the EPR violations are to be ruled out. This is because, as van Fraassen's paper shows, the idea of common cause (Reichenbach 1956) can be identified with that of hidden variable, as in Bell's theorem (Bell 1964). Thus, van Fraassen argues, postulating the existence of (screening-off) common cause events for the EPR correlations leads to the Bell inequalities, which are known to be empirically violated. One should then conclude, following the very consequences of Bell's theorem, that common cause explanations of EPR are not a possibility, i.e. that the hidden common cause variable that such accounts presuppose simply does not exist.

Such views attracted huge attention at the time and gave rise to a large literature on whether the idea of common cause is sensible and useful a notion to explain the EPR correlations. The general agreement being, as already pointed out, that

Financial support is gratefully acknowledged from BBVA Foundation, research project "Causality, Locality and Free Will in Quantum Mechanics", and Spanish Ministry of Economy, Industry and Competitiveness, project FFI2014-57064-P.

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G. Hofer-Szabó, L. Wroński (eds.), *Making it Formally Explicit*, European Studies in Philosophy of Science 6, DOI 10.1007/978-3-319-55486-0_8

EPR correlations cannot be accounted for in terms of common causes. Not that van Fraassen's derivation of the Bell inequalities was not contested at all. For instance, Hofer-Szabó et al. (2002) criticised the argument in "Charybdis of Realism ..." on the grounds that van Fraassen's definition of common cause does not exactly match that of Reichenbach's original proposal. In particular, van Fraassen's common causes are defined to be a rather restricted kind of events, which are required to screen-off two or more correlations at once. (These are so-called *common*-common causes, in contrast to Reichenbach's original *simple*, or *separate*, common causes.) Further refined versions of van Fraassen's original derivation have nevertheless reached similar conclusions than that in "Charybdis of Realism ...", reinforcing the idea that Reichenbachian common causes cannot account for the EPR correlations.[1]

Typical derivations of the Bell inequalities presuppose a common cause on to which several constraints and restrictions are set. Constraints on the postulated common causes are intended to reflect standard requirements of a generic physical system, including temporal order of causal relations or locality considerations. As a result, some version of Bell's *factorizability*—and therefore of a Bell-type inequality—is derived. The strength of such arguments relies thus on the plausibility of the conditions imposed on the common causes. There is, for instance, an extensive literature regarding the idea of locality, particularly concerning the intuitions leading to the concept of physical locality, the characterisation of the concept itself, its implications and whether it may be appropriately captured and characterised in terms of probabilistic relations.

Less attention has been paid to the requirement that the EPR experimenters do take free independent decisions at the moment of setting up the EPR apparatus for measurement. Roughly, this is usually taken to entail that the events representing the experimenters' decisions, and the foregoing corresponding free acts, be causally independent of the hidden variables. This is usually expressed by means of the so-called *No-conspiracy* condition—I shall in what follows refer to this condition, more neutrally, as *Measurement Independence*—, a probabilistic expression which is in some occasions taken to be necessary for free will.[2]

Rejecting *Measurement Independence*, however, is still an interesting option. Indeed, we might have good reasons for entertaining this possibility, as I already suggested in San Pedro (2013). These are mainly related to the different fashions in which *Measurement Independence* can be violated. The aim of this paper is thus to discuss and elaborate further some of the implications resulting form the rejection of *Measurement Independence*. In particular, the paper is concerned with a specific way the condition is violated, as a consequence of the rejection of two specific assumptions about the presupposed causal order and space-time arrangement of the events involved in the EPR picture.

[1] See, for instance, (Graßhoff et al. 2005) for a more recent example.

[2] Reference to 'free will' in this context is usually set aside in favour of more general stronger claims about 'world (or cosmic) conspiracies' instead. The exact relation between the requirement of *Measurement Independence*, 'free will' and 'world conspiracies' will be addressed more in detail in what follows.

The paper is divided in two parts. First, I shall review briefly the arguments for the requirement of *Measurement Independence* in the EPR context. Sections 8.2 and 8.3, in particular, provide an account of the general structure of the problem and the different arguments against *Measurement Independence* respectively, with special emphasis on the arguments as regards specific space-time and causal presuppositions behind it. In the second part of the paper I take on the implications of the actual violation of *Measurement Independence* as a consequence of the rejection of such space-time and/or causal assumptions. Here, the three resulting causal models initially hinted in San Pedro (2013) are discussed. The paper closes with some brief remarks on the issue.

8.2 Free Will, Conspiracy and *Measurement Independence*

Measurement Independence is the requirement that common causes C postulated to explain the EPR correlations be probabilistically independent from the corresponding measurement operations m_i performed on either wing of the experiment, i.e.

$$p(m_i|C) = p(m_i). \tag{8.1}$$

(I will write m_i for a generic measurement operation in an EPR experiment, with $i = L, R$ indicating that measurement is performed on the left and right wings of the experiment respectively. Similarly, in what follows, O_i, with $i = L, R$, will denote generic outcomes of the experiment.)

That Equation (8.1) must hold in any common cause explanation of the EPR correlations is often justified by the fact that EPR experimenters act freely to choose which specific measurements to perform each time. This requirement for free will in itself does not seem to be at all controversial. In particular, it seems desirable that any theory we propose that aims at a description of nature and that may include or refer to our (human) interaction with it, be consistent with the idea of free will—unless, of course, we discard the possibility of free agents from the very start. A more interesting matter concerns the issue as to how to represent appropriately the idea of free will within the theory, be it as a piece of mathematical formalism, as some set of background assumptions or presuppositions, etc. Addressing such issues however would take us far from our purpose here, since we are just concerned, at least in a first instance, with the more specific question whether there is indeed a relation between *Measurement Independence* and the idea of free will.

So does Equation (8.1) adequately represent a requirement related to the preservation of free will in the EPR context?

Many would claim already that this actually is not the right question to ask. For perhaps *Measurement Independence* has nothing todo with us humans having freedom of will, really, but rather with the idea that there be no (cosmic) conspiracies. As I will suggest later, however, these two claims are related, one being the generalisation of the other, i.e. claims about conspiracies are a generalisation of claims about the lack of free will. Let me then start with the arguments regarding the more specific requirement of free will.

So, once more, is this really so, i.e. is *Measurement Independence* really a requirement about free will? This question is very seldom addressed in the literature. In most derivations of the Bell inequalities the assumption of *Measurement Independence*—or for that matter *No-conspiracy*—is usually introduced rather uncritically and without proper justification. In particular, why is it that *Measurement Independence* guarantees the preservation of free will, or the lack of world conspiracies, is almost never addressed.

I have discussed the issue in some detail before in San Pedro (2013). The arguments there actually point to a conceptual independence between *Measurement Independence* and free will. We need not review such arguments in detail here but perhaps a brief sketch of them is in order—especially since the discussion that follows draws on one of these specific arguments.

In (San Pedro 2013) I point out in the first place that there are at least two ways to motivate a close relation between a statistical conditions such as *Measurement Independence* and the idea of free will. Namely, one may want to build an account of free will in terms of probabilistic relations from scratch—e.g. by defining acts of will in the first place and then providing a formalism which is able to accommodate dependence/independence between them. Alternatively, one may take the less ambitious option of identifying central features associated to free will which may have a more or less straightforward translation into probabilistic terms. Causation, or causal relations, seem like a good candidate if we are to pursue this later strategy. In fact, the notion of free will involves and presupposes a number of causal assumptions.

Thus, by paying a closer attention to those causal presuppositions behind the idea of free will which carry over to the formulation of *Measurement Independence*, we are in a position to address whether the two are indeed related or not.[3] In San Pedro (2013) I identify three such causal assumptions. I note that for *Measurement Independence* to represent some idea of free will one needs to assume (i) that there is a faithful connection between causal relations and statistical relations, i.e. *cause-statistics link* assumption, (ii) that the events involved have a precise fixed temporal arrangement, i.e. *time order* assumption, and (iii) that there are no causal influences *at all* between the postulated common causes and the events representing the corresponding settings of the experiment (and therefore between the common cause and the experimenters decisions), i.e. *no-cause* assumption (San Pedro 2013, pp. 92–94).

[3]I would even say that it is indeed the fact that these assumptions behind the idea of free will carry over to *Measurement Independence* what it is most often seen as justifying that the later stands for the former. And my point in San Pedro (2013) is precisely that such assumptions are not well grounded and can all be challenged.

All the above assumptions can be challenged on their own grounds to show that the putative link between the notion of free will and *Measurement Independence* is, if at all, weaker than initially supposed. Since in what follows I shall expand on the original argument concerning assumption (ii), i.e. *time order*, to the more general case of world conspiracies (see below), let me just briefly comment on assumptions (i) and (iii) above. Starting with the assumption that there is a faithful correspondence between causal relations and probabilistic statements it is clearly a strong idealisation. It is worth noting however that we need this assumption to be in place if our aim is to give causal explanations of correlations at all. Thus, we must assume the *cause-statistics link* even if it is not fully justified to do so if we attempt to provide a causal explanation of EPR correlations (San Pedro 2013, pp. 94–95). As regards assumption (iii) above, i.e. *no-cause*, it entails that the postulated common cause is either a deterministic common cause or at least a total cause of the measurement settings. In the face of it, this seems to be too strong an assumption (San Pedro 2013, pp. 99–100).

Despite the conclusion suggesting there is no conceptual connection between *Measurement Independence* and the idea of free will, thus casting doubts on *Measurement Independence* as an adequate requirement in the derivation of the Bell inequalities, it may be pointed out that the discussion—and therefore the conclusions as well– misses the point. For, it may be argued, it is not *free will* actually what *Measurement Independence* stands for but rather a more general idea related to the lack of a world (or cosmic) *conspiracy* (by which EPR measurement settings would be pre-established by a hidden variable in their past history).[4] More precisely, one can claim that it is not free will, in fact, what is behind the justification of Equation (8.1), but just the intuition that the world is not such that it conspires to pre-set measurement choices in an EPR experiment, regardless of how are those actually decided, i.e. be it by means of random radioactive devices, lottery boxes, some computer routine involving random numbers with no need for human interaction or operation, or even by means of human (free) decisions. In this view, thus, lack of free will would only be one very specific way among other possibilities a world conspiracy may show-up in a theory.

Under this more general approach we need to concentrate then on the alleged correspondence between *Measurement Independence* and the lack of a world conspiracy. Just like before, we may ask, does *Measurement Independence* need to be required in order to exclude a world conspiracy?

Again, and just like in the case of free will as a justification for *Measurement Independence*, the question above is very seldom addressed in the literature. I shall tackle the issue only briefly here. In particular, I shall generalise one of the arguments offered in San Pedro (2013), as noted above, in relation to *Measurement Independence* and free will to claim that requiring the world to be free of conspiracies does not necessarily mean that the condition of *Measurement Independence* is to be in place. The actual argument, as we shall see below, exploits

[4]This is, by the way, where the origin of the terminology *No-conspiracy* can be traced back to.

two specific background assumptions behind the requirement of *Measurement Independence*, related to the space-time arrangement of events in the EPR scenario. As a consequence, I shall conclude that it is not the case that violations of *Measurement Independence* entail any sort of world conspiracy, and therefore by contraposition that we can make sense of (common cause) causal pictures of EPR which feature such violations explicitly.

8.3 Temporal Order and Causal Order

Measurement Independence, as we have seen, is a probabilistic independence requirement with a straightforward causal grounding (and interpretation). Namely that common causes C postulated to explain the EPR correlations be causally independent of measurement operations m_i which lead to the correlated outcomes O_i. This interpretation however involves further assumptions related among other things to the specific time arrangement of events in an EPR experiment as well as, more generally, to how causal relations are to be understood.

(This last sentence is deliberately left vague. There are a number of causal assumptions onto which the referred interpretation of *Measurement Independence* is grounded. For instance, one needs to assume that causal relations, or the lack of them, are faithfully represented by probabilistic expressions, be it correlations in case of causal dependence, or probabilistic independence in case of causal independence. In what follows however I shall only concentrate on one such assumption, specifically related to the direction of causation. The reason for this is that, as we shall see, it is this particular assumption that can help us make sense of the other presupposition discussed here, about the temporal arrangement of events in the EPR scenario.)

Starting with the more specific assumptions behind *Measurement Independence*. The causal independence between the postulated common cause C and the measurement operations m_i presuppose a particular (fixed) time ordering of the events involved. More precisely, common causes are assumed to take place *before* measurement operations do (and therefore before any outcome is registered).

Let us call this presupposition *Time Order*:

Presupposition (Time Order) *The temporal arrangement of events in EPR is such that postulated common causes C take place* before *measurement operations m_i in both wings of the experiment do.*

The meaning of 'before' above amounts to an event 'being in the past' of the other, i.e. laying within the corresponding backwards light-cone. The actual time arrangement presupposed by *Time Order* results in the light-cone structure of Fig. 8.1.

The presupposition of *Time Order* above is rooted in the intuition that common causes are just hidden variables aimed at completing the otherwise incomplete description of the EPR phenomena offered by quantum mechanics—and by

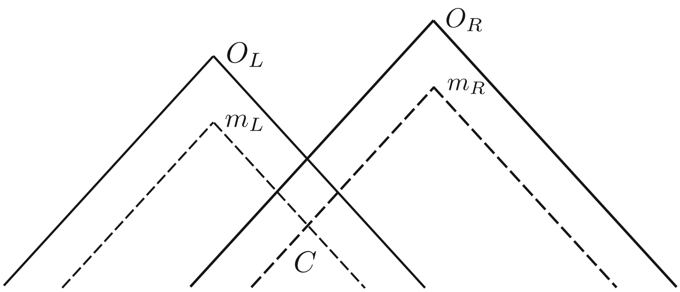

Fig. 8.1 *Time Order* demands that common causes C be in the past of measurement operations m_i $(i = L, R)$ in both wings of the EPR set-up (and therefore in the past of measurement outcomes O_i $(i = L, R)$ as well)

extension, therefore of any quantum phenomena.[5] As such, they are supposed to be a "missing" part of the quantum mechanical description of the singlet state, i.e. some missing bit of the actual (real) singlet state itself. This so close a relation to the actual singlet state is what seems to warrant the assumption that such hidden variables, i.e. common causes, need to be spatio-temporally located, if not at the very same source—where the singlet state sits—, in its (very) close vicinity. That is, in the intersection of the measurement operations' backwards light-cones.

As it happens *Time Order* is rarely discussed in the literature and very often assumed only implicitly. I shall suggest in a moment however that the particular temporal arrangement of events presupposed is not the only available option. In particular, causal models can be conceived in which this particular temporal order of events is altered.

Before going through such examples, let us discuss a further more general assumption behind *Measurement Independence*. It has to do with how actual causal relations propagate, and more precisely with the direction of causation. Indeed, for the above interpretation of *Measurement Independence* to make sense at all one needs to presuppose that causes *always* lie in the past of their effects. Let us call this presupposition *Causal Order*:

Presupposition (Causal Order) *Causes propagate* always *forward in time, i.e. causes* always *precede (temporally) their effects.*

Causal Order as formulated above seems closely related to our previous *Time Order* presupposition. In fact, they are related but only in the sense that presupposing *Time Order* in the usual attempts to provide causal explanations of EPR correlations does only make sense in the context of *Causal Order*. In other words, the particular temporal arrangement of events demanded in *Time Order* is a consequence of the assumption that *all* causes propagate forward in time. This is

[5]This is indeed the view defended by Bas van Fraassen in his influential "Charybdis of Realism ..." (van Fraassen 1982).

not however a *logical consequence*. Indeed, the two presuppositions are logically independent and, as we will see, can each hold or fail regardless of the other. Failure of any of them, or both, will also entail a failure of *Measurement Independence* in any case.

What *Causal Order* practically does is to rule out *any* possibility of backwards in time causation in our causal picture, whatever the particular time arrangement of events is. It is in fact what our most robust commonsense intuitions about causal relations seem to recommend. In the particular case of the EPR correlations then, *Causal Order* bans the postulated common causes to influence events in their past, or else be influenced by any events in their future—such as for instance measurement operations (in case *Time Order* is also in place, of course). Once more, this is usually taken to be the correct and most natural way to think about causal influences in the EPR scenario. Some authors disagree however and prefer to leave open the possibility that some causal relations may propagate backwards in time.[6]

In sum, requiring *Measurement Independence* involves a combination of an assumption about the temporal order of events, i.e. *Time Order*, as well as an assumption about the direction of causal influences, i.e. *Causal Order*.

8.4 Three Common Cause Models

As noted above, *Time Order* and *Causal Order* are logically independent statements which can each hold or fail on their own grounds, regardless of the other. And in fact rejecting either of them separately, or both of them at the same time, yields at least three different causal pictures or models, as suggested in San Pedro (2013). Obviously, all such causal models will violate *Measurement Independence*. Table 8.1 (page 154) displays the logical structure, when it comes to the *Time Order*

Table 8.1 Common cause models where *Measurement Independence* is not satisfied do violate either *Time Order* or *Causal Order* presuppositions, or both. The standard common cause structure assumed in the usual derivations of Bell's theorem (i.e. 'Standard Common Cause Model'), in contrast, satisfies both of these, and of course *Measurement Independence* as well

Time and causal order in common cause models			
	Measurem. Ind.	*Time order*	*Causal order*
CC Model 1	x	✓	x
CC Model 2	x	x	✓
CC Model 3	x	x	x
Stand. CC Model	✓	✓	✓

[6] As we shall see in a moment, a violation of *Causal Order* will not mean that *all* causal influences propagate backwards in time but just that *some* do. This will be in fact the source of some criticism as regards common cause models featuring a violation of *Causal Order*.

and *Causal Order* presuppositions, of each of the three common cause models discussed below, plus that corresponding to the common cause model assumed in the usual approaches, which I refer to as ‘Standard Common Cause Model’.

Common Cause Model 1: A first causal picture results from keeping the temporal arrangement of events assumed in standard treatments of causal explanations of the EPR correlations, i.e. what I called *Time Order* above, but rejecting the assumption that causal influences propagate *only* forward in time, i.e. *Causal Order*.

In other words, one may assume that, as usual, postulated common causes take place before *both* measurement operation events (in both wings), as well as of course before the outcome events. Again, that this is the right temporal sequence of events which a given run of an EPR experiment must feature is normally presupposed without further justification. Yet I cannot see any particular reason why this needs to be so.[7] With the *Time Order* assumption in place, nevertheless, the intuition is that violations of *Measurement Independence* can only make sense—with no world conspiracies involved—if the corresponding causal model features backwards in time causation.

In this picture then actual measurement operations m_i are (future) causes of the postulated common causes C, which are in turn causes of the measured outcomes O_i. Provided the common cause C is postulated to be an event in the remote past of both outcomes, i.e. an event located somewhere in the overlap of the outcomes backwards light-cones, all causal influences in the model will be completely local influences, hence avoiding conflict with special relativity (see Fig. 8.2).

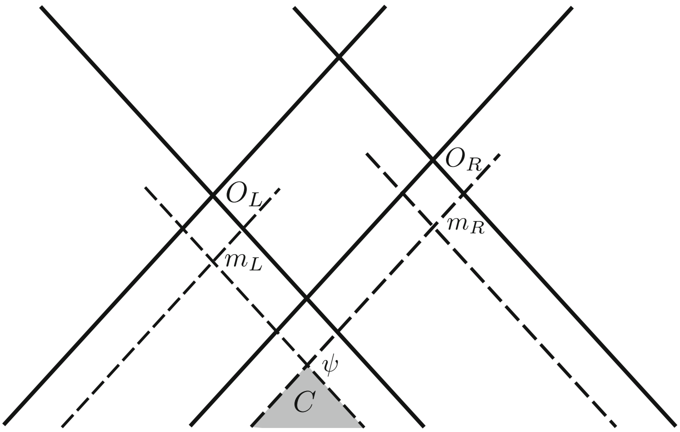

Fig. 8.2 Backward light-cone structure for measurement operations propagating causally backwards in time to influence the postulated common causes in their past. Common causes, in turn propagate, as usual forward in time to cause corresponding future outcomes

[7]However, rejecting *Time Order* would result in other different causal pictures (see causal models 2 and 3 below).

Problems with such a model will come obviously from the fact that some of the causal influences they feature propagate backwards in time. On the one hand, backwards causation is not really a preferred option in the relevant literature, as it is taken by most to be highly counter-intuitive. It is fair to say that some quite influential authors still keep this option open.[8]

This kind of causal models will also face difficulties related to the fact that *only some* of the causal influences in them propagate backwards in time. In particular, for such models to work they need to display a combination of causal influences propagating in both directions (of time), i.e. both backward and forward causal influences. (Note that saying that the model is a backwards causation model does not mean that *all* causal influences in it take place backward in time. To ensure that all causal influences took place backwards in time we would need to change—reverse—the time order of all events, which would probably take us to a full backwards in time causal model in which *Measurement Independence* would not be violated.)

The question is then, how can one tell, in a particular causal structure, which causal relations should actually take place forward time and which backward in time (and why these and not some others). Is seems, in particular, there is no way to identify in advance what events will feature causal influences in one or the other direction, i.e. there is no way to know when to expect one or the other. In the EPR case above, for instance, why should measurement operation events m_i, and not some other event, have the "privilege" of being able to propagate their causal influences backward in time?

Further worries may arise as well in relation to the possibility of facing paradoxical situations if we admit both forward and backward causal influences.[9] The causal picture above, for instance, leaves unspecified what kind of causal influences may the experiment's outcomes be associated to, i.e. whether they are causes propagating forward or backward in time. It would be perfectly fine not to worry about this if the outcomes would operate causally as usual, i.e. forward in time. However once we admit the possibility that one of them may propagate causally backwards in time we are open to paradox. In particular, it is perfectly conceivable in that case, say, that O_L in Fig. 8.2 has some causal influence on m_L, i.e. that an outcome has some causal influence on the measurement setting that gave rise to it in the first place.[10]

This would have undesired consequences. On the one hand, it would be a clear threat to the attempt of the model to save free will since the experimenter's choices when setting the measurement apparatus would no longer be free—they would be

[8]Classical references to retrocausal pictures include Sutherland (1983), de Beauregard (1987) or more recently Price (1994, 1996). Huw Price, for instance, has gone as far as to argue that the characteristic time-symmetry of quantum mechanics (and of microphysics in particular) may imply, given some further assumptions about the ontology of the theory, the existence of backwards in time causation, or retrocausality, as he terms it (Price 2012).

[9]I must thank a reviewer for hinting this further kind of difficulties.

[10]Note that we cannot rule out this possibility completely just by looking at the other relevant probabilistic relations among O_L and m_L. In fact, we should expect them both to be correlated.

caused by the outcome. On the other hand, allowing O_L to causally influence m_L would result in the model featuring a causal loop between these and the common cause C. All these are problems that any retrocausal model of EPR correlations needs to address.

Worries as the above also reveal the close relation between *Time Order* and *Causal Order* and suggest further causal models resulting from a violation of the requirement that the time arrangement of events follows the specific structure demanded in *Time Order*. So, why not considering actual violations of *Measurement Independence* via a failure of (at least) *Time Order*? In other words, why not revise the particular time arrangement of events fixed by *Time Order*, and consider possible modifications of it? This would lead to at least two further causal models.

Common Cause Model 2: As a first option, we could consider causal structures which violate *Measurement Independence* via a failure of *Time Order* only. That is, causal models built without the premise that the postulated common cause C be in the past of both measurement operations m_i and corresponding outcomes O_i, while keeping the intuition that, in effect, causal influences propagate exclusively forward in time, i.e. satisfying *Causal Order* above.

A causal model along these lines is discussed in San Pedro (2012), for instance. There, a common cause C is postulated to take place just in between the actual measurements m_i and the corresponding outcomes O_i. That is, the common cause is now taken to lie in the future of measurement operations m_i but in the past of the resulting EPR outcomes O_i.[11] In terms of space-time structure, the model postulates a common cause which ought to be located somewhere in the union of the two regions defined by the double light-cones formed by each measurement operation m_i and the corresponding outcome O_i (see Fig. 8.3).[12]

With this new temporal arrangement of events therefore, measurement operations can well be thought to be causally relevant for the postulated common cause, which in turn would be responsible of such and such outcome being observed. And all causal influences propagate forward in time. This has as a consequence that some of the causal influences in the model will clearly turn out to be non-local. This becomes obvious from the fact that, as already pointed out, postulated common causes C shall now be located somewhere in the union of the double light-cones formed by the measurement operations m_i and the corresponding outcomes O_i (see again Fig. 8.3). And since these two regions are space-like separated any causal influence from any of them on the distant wing outcomes will forcefully be non-local.

[11]Obviously, this is not the only temporal arrangement possible. *Time Order* could be violated as well by altering the order between measurements and outcomes, and leaving the common cause in the past of both, just as it is standard. The problem with such a structure, of course, is that it is very difficult to think of outcomes taking palace (or being observed) before measurements have been performed.

[12]This model, of course, needs to assume that there is some lapse of time—or rather some region of space-time—, however little this may be, between the performance of a measurement and the occurrence of the corresponding outcome. See San Pedro (2012) for details.

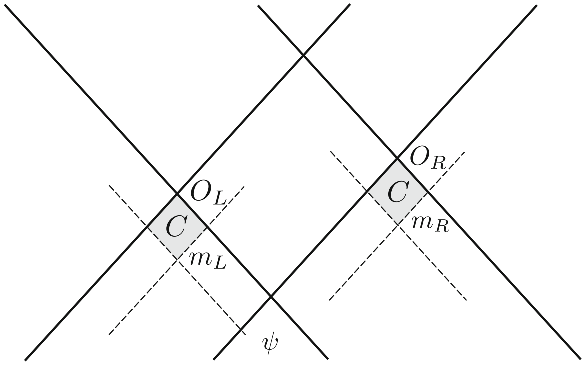

Fig. 8.3 Backward light-cone structure for common causes C located in the future of measurement events m_i, but in the past of resulting outcomes O_i. All causal influences propagate, as usual, forward in time

Quantum non-locality is not new however, and one may even argue that it is not really such a strange feature any more. Critics may want to note nevertheless that simpler non-local explanations of the EPR correlations are already available without the need to refer to the notion of common cause at all—such as non-local direct causal models, for instance. In other words, why do we need common causes for the explanation of EPR correlations at all, if they just seem to constitute a further unnecessary complication?

It is worth noting, in response to such criticism, that common cause models as the above might have more to offer than simpler direct cause models. In the case of the model outlined here, for instance, the fact that measurement operations are taken to be explicit causal relevant factors for the EPR outcomes can be seen as the model telling us something about measurement in quantum mechanics. Namely, that quantum measurement is a causal, generally non-local, process.

Finally, let me point out that endorsing a model along these lines can also be motivated by some results in algebraic quantum field theory (AQFT). In particular, for instance, it has been recently shown that (the equivalent to) common cause events postulated to explain distant correlations in AQFT exist, but these must be located in the union of the correlated events backward light-cones, i.e. a so-called "Weak Reichenbach's Common Cause Principle" holds in AQFT (Rédei and Summers 2002). This of course does not mean that the common cause events be necessarily located precisely in the shaded double-cone regions in Fig. 8.3 above. However, that this may be so certainly remains an open possibility.

Common Cause Model 3: Rejecting both *Time Order* and *Causal Order* at the same time results in yet another causal structure displaying backwards in time causation (just as in the first causal model discussed above). In this case however the presence of backwards in time causal influences will only make sense if the alteration of the temporal arrangement of events originally fixed by *Time Order* is just different than the one assumed in our previous Common Cause Model 2. In particular, putative common causes C need now be postulated as events located in the future of both measurement operations m_i and corresponding outcomes O_i (see Fig. 8.4).

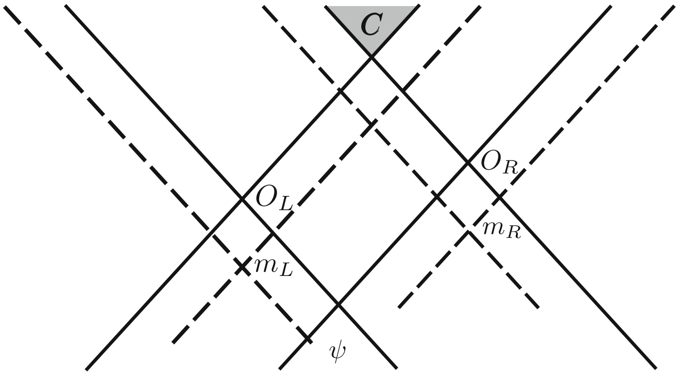

Fig. 8.4 Backward light-cone structure for common causes in the future of both measurement operations and outcome events. Common causes operate backwards in time to cause corresponding events

Also as in the first model above, causal influences shall now turn out to be completely local as long as the postulated common cause is located far enough in the future of the experiment outcome events. Locality will be assured, more in particular, if the common cause *C* is assumed to lie in the overlap of the EPR outcomes future light-cones (see again Fig. 8.4). We can see then, once more, that locality is achieved at the cost of introducing backwards in time causation in our models. Just as in Model 1, this causal picture can avoid conflict with special relativity fairly easily.

Obviously, we shall now also face similar problems to the ones encountered with Model 1, related precisely to backwards causation. Namely, we shall face the charge that backwards in time causal influences are highly counterintuitive. But also, and just as with Model 1, we shall now face the fact that cannot provide a satisfactory account of how backward in time influences can be identified precisely. In particular in this model the causal structure also features now a combination of forward and backward causal influences. And again there does not seem a good way to tell what this precise combination is, i.e. which events exactly will propagate causally forward in time, and which will do it backwards. Once more the only reply available to such criticism seems to be that it is the specific temporal arrangement of events that the model presupposes what fixes the specific combination of events propagating either forward or backward in time.

8.5 Conclusion

I have revised above three common cause models all of which violate *Measurement Independence*, and therefore avoid the implications of Bell's theorem as regards the existence of common cause explanations of EPR correlations. The three models were obtained each as a result of rejecting two further presuppositions behind *Measurement Independence*. Namely, that the temporal arrangement of events is a given specific one—that in Fig. 8.1—, which needs to be kept fixed, i.e. *Time Order*, and that the direction of causal influences is also fixed (and taken to be forward in time), i.e. *Causal Order*.

The discussion above highlighted, in each case, a particular aspect of the quantum description of the EPR experiment and/or its phenomenology. For instance, causal pictures in which *Causal Order* was violated, i.e. Models 1 and 3, showed that the tension between causality and non-locality (most commonly taken to be expressed by the implications of Bell's theorem) can be dissolved once we admit the possibility that backwards in time causal influences may take place, and regardless of the specific space-time arrangement of the events involved. However, backwards in time causation suffers from its own problems.

On the other hand, preserving our usual intuitions about the direction of causation, but allowing instead that the temporal arrangement of events fixed by *Time Order* be altered results in a causal structure where some of the causal relations happen to be non-local. Despite the well known difficulties that non-locality introduces, such a model might be useful to investigate the precise (causal) role of measurement in quantum mechanics.

To close, aside the above specific issues the three models discussed here raise, what they show, above all, is that it makes perfect sense to consider violations of *Measurement Independence* which do not convey in any way world conspiracies, or conflict with us having freedom of will at all.

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