Time-symmetry without retrocausality: how the quantum can withhold the solace

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Abstract

It has been suggested that some of the puzzles of QM are resolved if we allow that there is retrocausality in the quantum world. In particular, it has been claimed that this approach offers a path to a Lorentz-invariant explanation of Bell correlations, and other manifestations of quantum "nonlocality", without action-at-a-distance. Some writers have suggested that this proposal can be supported by an appeal to time-symmetry, claiming that if QM were made "more time-symmetric", retrocausality would be a natural consequence. Critics object that there is complete time-symmetry in classical physics, and yet no apparent retrocausality. Why should QM be any different?

In this note I call attention to a respect in which QM is different, under some assumptions about quantum ontology. Under these assumptions, the option of time-symmetry without retrocausality is not available in QM, for reasons intimately connected with the fundamental differences between classical and quantum physics (especially the role of discreteness in the latter).

1 Introduction

A number of writers have suggested that some of the puzzles of quantum mechanics (QM) are resolved if we allow that there is retrocausality in the quantum world. In particular, it has been claimed that this approach offers a path to a Lorentz-invariant explanation of Bell correlations, and other manifestations of quantum "nonlocality", without action-at-a-distance (see, e.g., [2]–[6], [9]–[18]). Some of these writers have suggested that an argument in favour of this proposal may be found in considerations of time-symmetry: that if QM were made more time-symmetric, retrocausality would be a natural consequence. Against the latter claim, critics object that there is complete time-symmetry in classical physics, and yet no apparent retrocausality. Why should QM be any different?

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In this note I call attention to a respect in which QM may indeed be different, under some assumptions about quantum ontology. Roughly, the exclusions seem to be instrumentalism on the one side, and no-collapse versions of ontic realism about the wave function on the other. For other views, it turns out that the intuitively comfortable option – time-symmetry without retrocausality – is not on the table in QM, for reasons intimately connected with the fundamental differences between classical and quantum physics; especially the role of discreteness in the latter.

The crucial issue is whether the discreteness is regarded as "all there is", or whether continuity is also provided in the ontology, e.g., in the form of a wave function, ontically intepreted. In the former case but not the latter – i.e., roughly, if we are any sort of realist other than an Everettian or a Bohmian – we do need to make a choice between time-symmetric ontology and retrocausality in QM, in a manner not true of classical physics.[1]

It is a standard assumption of Bell's Theorem [1] and other No Hidden Variable theorems in QM that there is no retrocausality: that hidden variables (HVs) are independent of future measurement settings. The present argument clarifies the relationship between this assumption and time-symmetry, and shows that on some but not all conceptions of the preferred form of a HV theory, there is indeed a tension between the two.

2 Polarization – classical and quantum

2.1 The classical case

We first consider the standard description in classical electromagnetism (CEM) of the apparatus shown in Figure 1. A beam of light, linearly polarized in direction τ_R, is directed towards a ideal polarizing cube set at angle σ_R. CEM predicts that the beam will split into two output beams. The *transmission* beam, here labelled $\mathbf{R} = 1$, will have an intensity $\cos^2(\tau_R - \sigma_R)$ times that of the input beam. The *reflection* beam, here labelled $\mathbf{R} = 0$, will have an intensity $\sin^2(\tau_R - \sigma_R)$ times that of the input beam. Thus in the case in which $\tau_R = \sigma_R$, all the energy goes on the transmission beam; in the case in which $\tau_R = \sigma_R + \pi/2$, all the energy goes on the reflection beam; and other cases are distributed between these extremes, in a continuous fashion. The transmission ($\mathbf{R} = 1$) and reflection ($\mathbf{R} = 0$) beams have linear polarization in directions σ_R and $\sigma_R + \pi/2$, respectively.

Figure 2 shows the corresponding behaviour in the reverse case – that is, when beams of linearly polarized light with the appropriate polarization angles and intensities are directed into the polarizing cube, through what were previously the transmission and reflection output channels. (The diagram has

[1] The situation for Everettian and Bohmian views is less clear. There may be other reasons to think that they cannot entirely combine time-symmetry and one-way causality. (I discuss the case of the Bohm view briefly in §4.5 below.) But they escape a particularly sharp argument for the incompatibility of these options that applies to other realist views.

been mirror-reversed, to preserve the convention that inputs come from the left and outputs go to the right. HEre) If the input on the transmission channel, $\mathbf{L} = 1$, is polarized in direction σ_L with intensity $\cos^2(\tau_L - \sigma_L)$, and the input on the reflection channel, $\mathbf{L} = 0$, is polarized in direction $\sigma_L + \pi/2$ with intensity $\sin^2(\tau_L - \sigma_L)$, then there is an output beam with intensity 1 and polarization τ_L, in the direction of the input beam in the original experiment.

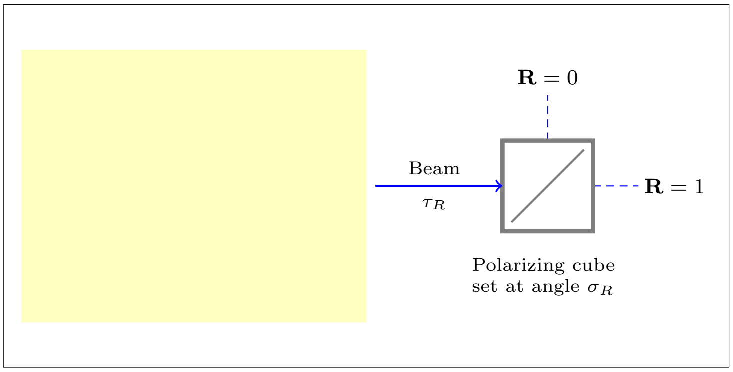

Figure 1: The classical set up – right.

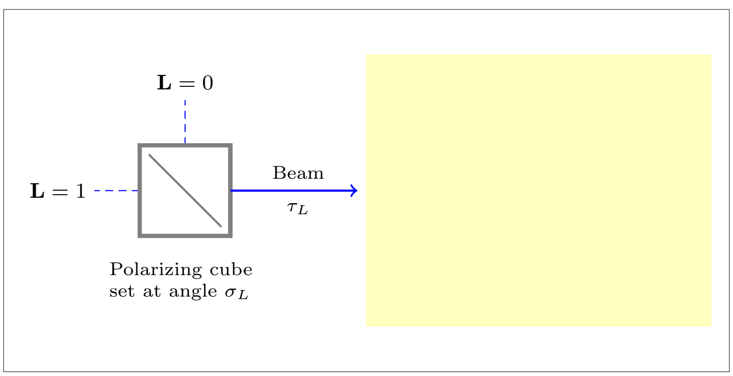

Figure 2: The classical set up – left.

2.2 The quantum case

Figures 3 and 4 show the quantum versions of these experiments, in the single photon case. For the moment, to make the interesting difference with the classical case as sharp as possible, we shall assume that the outputs at $\mathbf{R} = 1$ and $\mathbf{R} = 0$ and the inputs at $\mathbf{L} = 1$ and $\mathbf{L} = 0$ are now discrete, in the sense that the photon leaves or enters the apparatus on one channel or other. (More later on the case in which the input and/or output may be a superposition.) This requires that the factors $\cos^2(\tau_R - \sigma_R)$ and $\cos^2(\tau_L - \sigma_L)$ now represent probabilities, rather than intensities.[2] Thus in Figure 3, a photon with polarization τ_R has a probability $\cos^2(\tau_R - \sigma_R)$ of being detected on the $\mathbf{R} = 1$ channel, and a probability $\sin^2(\tau_R - \sigma_R)$ of being detected on the $\mathbf{R} = 0$ channel. (The intensity interpretation is recovered in the limit, as the numbers of photons goes to infinity.)

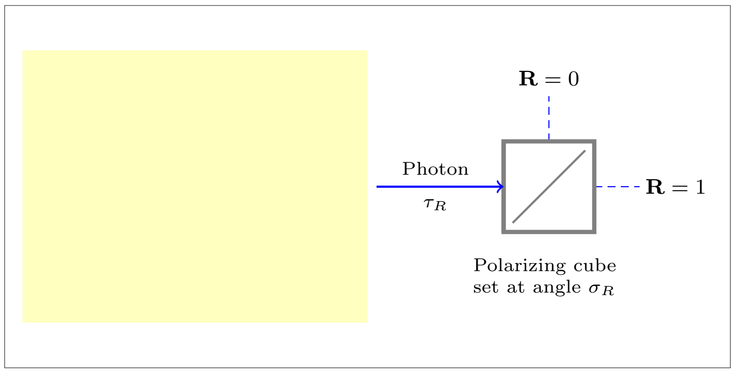

Figure 3: The QM set up – right.

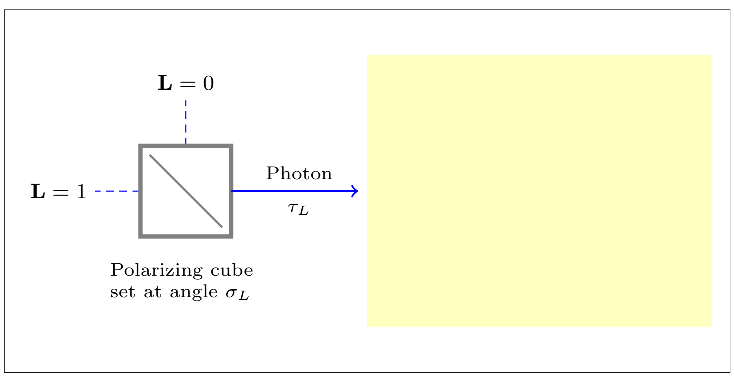

Figure 4: The QM set up – left.

3 Experimental control

We now consider the question of what can be controlled, in the CEM and quantum cases, by experimenters who control *only the polarizer settings,* σ_L

[2]There are some subtleties about what these probabilities amount to, on the input side – perhaps even about whether they are *probabilities* at all, on some understanding of probability – but I set those aside, for now.

and σ_R. (The reason for this restriction on what the experimenters control will become clear as we proceed.)

3.1 The classical case

Figure 5 shows the CEM version of experiment we obtain by combining the two previous cases. What interests us is the question of what control, if any, the lefthand experimenter, Lena, has over the intermediate polarization, *if she has no control over the inputs at* $\mathbf{L} = 1$ *and* $\mathbf{L} = 0$.

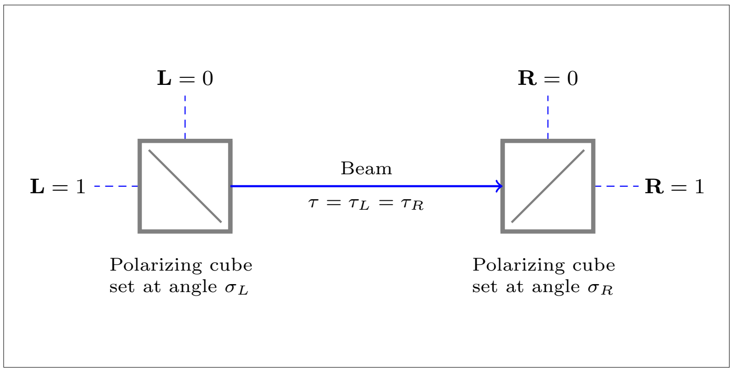

Figure 5: The full classical set up.

To put this question in a stark form, imagine that the inputs $\mathbf{L} = 1$ and $\mathbf{L} = 0$ are under the control of a Demon, who knows what setting σ_L Lena has chosen for her polarizer. It is not difficult to see that under these conditions the Demon can produce any intermediate polarization τ he wishes, by an appropriate selection of inputs. This follows directly from the time-symmetry of the CEM case: the inputs the Demon needs on the left are exactly the outputs Nature produces on the right, with intermediate polarization τ and right setting $\sigma_R = \sigma_L$.

Lena's lack of control of τ on the left, in the case in which the Demon controls the inputs, is exactly mirrored for her sister experimenter, Rena, on the right. The intuitive reason why Rena cannot control τ by varying the right polarizer setting σ_R is that (as we just noted) Nature is able to make up for any difference in σ_R by a difference in intensities of the output beams $\mathbf{R} = 1$ and $\mathbf{R} = 0$. In this case, τ doesn't shift, no matter how much Rena wiggles the setting σ_R. This is why there need be no retrocausality in this case, of course.[3]

To characterise this situation, I shall say that Lena has no *input-independent* control of τ, and that Rena has no *output-independent* control of τ. The im-

[3] For future reference, note that it does not follow that there *could not be* retrocausality. To block retrocausality altogether, Nature must behave as the mirror image of the perfect obstructive Demon. Imperfect Demons, who block some but not all forward influence on the left, correspond to ways in which Nature *might be,* to allow some retrocausality on the right.

portance of the notion of input-independence is that it mimics on the front end of the experiment precisely the question we need to consider on the back end, to think about the possibility of retrocausality. For on the back end, on the right, the experimenter has control of the setting, σ_R, but not the outcome. To think about retrocausality, as we have just seen, we need to think about what else she controls, if she controls only this much. Input-independence enables us to think about the analogous issue at the input end of the apparatus, and time-symmetry enables us to move from one case to the other. The next step is to consider these issues in the quantum case.

3.2 The quantum case

Figure 6 shows the analogous quantum case. (It will become clear in a moment why we should not assume that $\tau_L = \tau_R$, in this case.)

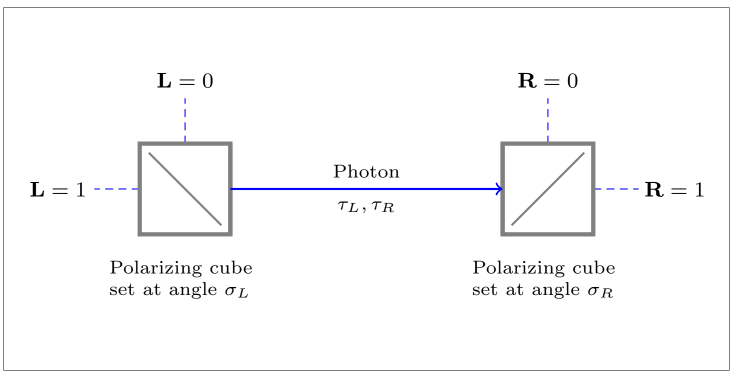

Figure 6: The full quantum set up.

It is a striking fact that in this quantum case, Lena has more control over the left-polarization τ_L than in the classical case, even if the Demon retains control of the inputs at $\mathbf{L} = 1$ and $\mathbf{L} = 0$. Of course, the Demon can refuse to provide any photons at all, in which case nothing emerges from the Lena's apparatus. But if we assume that the Demon shares with Lena the goal of emitting photons to the right, Lena now has complete control of τ_L, save only for a factor of $\pi/2$. For if Lena sets her polarizer to angle $\sigma_L = \tau_L$, the Demon's only choices are to send in a photon via $\mathbf{L} = 1$, in which case it emerges with polarization τ_L; or to send in a photon via $\mathbf{L} = 0$, in which case it emerges with polarization $\tau_L + \pi/2$.[4]

Thus in the notation introduced above, Lena has *input-independent* control of τ_L, up to a factor of $\pi/2$, by means of her control of the left setting, σ_L. Input-

[4] We are still assuming that the Demon cannot supply a superposition of $\mathbf{L} = 1$ and $\mathbf{L} = 0$. The physical direction of the $\mathbf{L} = 0$ depends on σ_L, but this creates no additional difficulty for the Demon, under our assumption that he knows what setting Lena has chosen. (Here, as in many other places in this paper, I am indebted to Ken Wharton.)

independent control is a new feature of the quantum case, resulting directly from the discreteness condition QM imposes on the inputs. (As we shall see, it disappears if we restore continuity at this point, by allowing the Demon to input superpositions of $\mathbf{L} = 1$ and $\mathbf{L} = 0$.)

In the classical case, we noted not only that Lena does not have input-independent control of τ, but also that the same is true for Rena, on the right. She does not have output-independent control of τ, because Nature will always absorb any change she makes to the setting σ_R by means of a change in the output intensities, thus requiring no change in τ. As we noted, this is why there is no retrocausality in the classical case (despite complete time-symmetry).

Let us now assume that the ontology of the quantum case is time-symmetric, in the sense that there is an element of reality, or beable, which stands to σ_R, $\mathbf{R} = 1$ and $\mathbf{R} = 0$ in precisely the same way that τ_L stands to σ_L, $\mathbf{L} = 1$ and $\mathbf{L} = 0$. Let τ_R in Figure 6 now denote this beable. It now follows by symmetry that Rena has precisely the same output-independent control over the value of this beable as her sister has over the value of τ_L. She, too, can determine its value up to a factor of $\pi/2$, no matter what Nature does with the outputs on $\mathbf{R} = 1$ and $\mathbf{R} = 0$.[5] In particular, this means that if Rena changes the setting σ_R by any amount $\rho \neq \pi/2$, this will result in a *different* value of τ_R for any subsequent photons. In counterfactual terms, it seems intuitively reasonable to say of any particular case that if she *had* chosen $\sigma_R + \rho$ rather than σ_R, the value of τ_R would have been different. Thus, intuitively, she has retrocausal control over τ_R, up to the factor of $\pi/2$.

Thus, as we wanted to show, time-symmetric ontology requires retrocausality, in this case, for reasons not present in CEM. The heavy lifting here is done by the requirement that the outputs at $\mathbf{R} = 1$ and $\mathbf{R} = 0$ be discrete, for it is this that ensures that Nature lacks the degrees of freedom required to absorb the difference of a change in σ_R entirely in the future. Given time-symmetry in the ontology, retrocausality then becomes a simple consequence of the dynamical laws.

4 Discussion

To clarify the scope and significance of this result, and the assumptions on which it depends, I want to conclude with a brief discussion of some ways in which it seems possible to evade the conclusion. (The following list is unlikely to be complete, and I welcome suggestions for additions.)

4.1 Make the ontology time-asymmetric

This option avoids retrocausality, but not the main claim of this paper, which is simply that in some interpretations of QM, time-symmetry does requires retrocausality, in a manner not true of CEM.

[5] For the moment, we are still assuming that Nature cannot choose a superposition of the two.

This option seems likely to incur an additional cost, on top of that of the time-asymmetry itself. Given any model with a time-asymmetric boundary-independent ontology of the required kind, there will be another model which is simply the time-reverse of the first. Unless there is some independent reason to prefer one model to the other – which would be, *ipso facto,* a reason to expect time-asymmetry in the domain in question – then the time-asymmetry will have introduced an undetectable fact of the matter into our ontology, which a symmetric model would avoid.

4.2 Avoid ontology altogether

The above argument does not go through if we deny that the usual quantum polarization, τ_L is a beable, or element of reality. Hence our conclusion can be avoided altogether by a sufficiently thoroughgoing instrumentalism about the quantum world. This escape route is not available to proponents of the Hidden Variable program, of course. (It is not even available to *opponents* of HVs, in so far as they are interested in the project of exhibiting supposedly undesirable consequences of the HV approach – in this context, they cannot begin by denying their opponents' basic premise.)[6]

4.3 Avoid the specific ontology of the example

A more subtle objection would be that the grounds for treating the usual quantum polarization τ_L as a beable rest on the assumption that there is no retrocausality. If the photon "already knows" σ_R, then it doesn't seem to need the full information carried by τ_L, in order to explain the correlations we find in the full experiment, for variable σ_L and σ_R – perhaps there is no such beable as τ_L. I think this is an interesting point,[7] but in the present context the objector shoots himself in the foot, by invoking retrocausality in order to block an argument in favour of retrocausality.

4.4 Restore continuity by allowing superpositions

As noted above, input-independent control disappears from the QM case, if we allow the Demon the option of introducing a photon in a superposition of the $\mathbf{L} = 1$ and $\mathbf{L} = 0$ cases. In this case, by an appropriate choice of input amplitudes on each channel, the Demon can produce any τ_L he wishes, whatever Lena's choice of σ_L. (As in the classical case, this follows immediately from a consideration of the time-reversed case, given the time-symmetry of the relevant quantum dynamics.)

[6] In [7], Evans, Wharton and I argue that this option should be regarded as analogous to the standard view of spacelike nonlocality, involving the same kind of action-at-a-distance (though timelike, rather than spacelike).

[7] Among other things, it seems to bear on the question as to whether a time-symmetric model should involve the two beables τ_L and τ_R, or better some single beable, dependent both on σ_L and σ_R, which would combine the role of both.

To avoid output-independence, and hence retrocausality, this option needs to be available to Nature in Rena's case. In most versions of QM, Rena can frustrate Nature, simply by making a measurement on the output channels. But some views have a loophole at this point. Everettians certainly do, for example, for in their picture, there is no single definite outcome, whatever the appearances in any single branch.

It might be objected that even without the Everett view, the option of producing a superposition of $\mathbf{R} = 1$ and $\mathbf{R} = 0$ is still available to Nature; a definite outcome only being needed when Rena makes a measurement.[8] This is true, but I think of limited use at this point, given the constraints of the problem. The task is to explain the correlations observed between inputs and outputs, in a quantum device of the kind depicted in Figure 6; and the issue is whether an explanation can be given using a time-symmetric intermediate dynamics and ontology, without admitting retrocausality. We have noted that in the analogous classical problem in Figure 5, the solution depends on the fact that the outputs may be continuously distributed between $\mathbf{R} = 1$ and $\mathbf{R} = 0$. In the quantum case, it is no help to point out that superposition may provide continuity "inside the black box", so long as the experimental outputs themselves remain discrete.[9] The Everett view gets off the hook by denying that the experimental outputs really *are* discrete, at the global level. Where there is discreteness in the final conditions of the experiment, however, it doesn't seem to make any difference whether it appears at the time of the measurement, or at some later time.

4.5 The de Broglie-Bohm view

For the Everett view, the wave function provides Nature with all the flexibility she needs to absorb the consequences of changes in σ_R, within a time-symmetric ontology, without requiring that they show up at earlier times. And the trick seems to be available to any view that takes an ontological view of the wave function. In particular, therefore, it is available to the de Broglie-Bohm (dBB) view,[10] despite the fact that this theory also provides discrete outputs and inputs. Like Everettians, Bohmians can consistently combine time-symmetric dynamics and ontology with one-way causality, at least so far as the argument above is concerned.[11]

As we have noted, however, the trick that enables Nature to avoid retrocausality in this case can be played in either direction. In the dBB picture, as

[8] Thanks to Richard Healey here.

[9] It is well-known that collapse models are time-asymmetric. This case thus illustrates one way in which a time-asymmetric ontology can avoid retrocausality; but this conclusion is not in tension with the claim that a time-symmetric ontology requires retrocausality, in the case in which the outputs are discrete.

[10] Or at least to most versions of it: in some versions, the wave function may not be ontic, in the required sense.

[11] I am setting aside the question as to whether the dBB approach can be applied to photons. One justification for this concession is that the argument of §3.2 could be recast in terms of spin, apparently.

in the classical case, Nature could in principle act like the perfect Demon in the kind of examples we have been considering, allowing retrocausation but not forward causation. It is a nice question whether the difference would be observable; or whether, as seems true in the CEM case, justification for the option that excludes retrocausality could be found in the low entropy initial conditions available to us in the laboratory. (The apparent difficulty concerning the latter point is that in the single-photon limit, we are operating well "below" the statistical domain, in which this notion of a special initial condition makes sense.) If not, then like the time-asymmetric models mention in §4.1 above, these views appear to break a symmetry at the cost of making it unobservable which way it is broken.[12] To avoid this cost, it might be felt desirable to aim for a symmetric model, allowing influence in both directions.

To address these issues, we need to step back a bit, and think about what is at stake. One of the attractions of examples like that of Figure 6 is that they make it easy to pose the relevant questions, without surreptitiously introducing a bias in one direction or other. The symmetries of the model make any bias easily visible.

"Intuitive causality" clearly involves such a bias: we find it natural to say that if Rena had chosen a different setting, that difference would have made no difference to the photon arriving from the left, but might have affected the result to the right; but very unnatural to say that if Lena had chosen a different setting, that difference would have made no difference to the photon departing to the right, but might have affected the input from the left. We have seen that if the ontology is time-symmetric, and the outputs at $\mathbf{R} = 1$ and $\mathbf{R} = 0$ are discrete, this asymmetry is unsustainable – we are forced to revise our view about Rena's case. But where does the intuitive bias come from in the first place? And what reason, if any, do we have in continuing to take it for granted, in a case such as the dBB theory?

Our simple model helps with the first of these questions. In the classical case, the obvious difference between Lena and Rena is that Lena controls both the σ_L *and* the inputs $\mathbf{L} = 1$ and $\mathbf{L} = 0$; whereas Rena controls only the setting σ_R. We introduced the Demon in order to restore symmetry, but what breaks symmetry, normally, is the fact that there is no Demon: on the contrary, experimenters control their inputs, too.[13]

But if this is the right story about the source of the bias in the classical case, it seems to cast doubt on our entitlement to retain the bias, in the single-photon case. Intuitively, Lena does have enough control over the classical input beams to ensure that they *would have been the same* (from the same directions, with the same intensities and the same polarizations), if she had chosen a different measurement setting. She does not have enough control over the behaviour of a single-photon source to ensure that *the same photon* would have entered the apparatus, with *the same properties,* if she had chosen a different measurement

[12]It wouldn't do to argue that the Demon would have to depend on incredible prearranged conspiracies, for the question is why these should be acceptable in one direction but not the other.

[13]A fact which relies on the availability of low entropy sources, presumably.

setting. "Intuitive" causality tells us that a different setting wouldn't have made any difference; but in this case, unlike in the classical case, the intuition isn't backed up by anything that Lena can actually *do.*

Again, our argument shows that the intuitive view *must* be wrong, given time-symmetry, in some versions of a QM account of this case. While the dBB theory is not one of those versions, escaping an argument for the conclusion that the intuitive view is mistaken is not the same as offering an argument that it is not mistaken. It is unclear what form the latter argument might take, for a proponent of the dBB view.[14]

Intriguingly, there are hints of an argument for the opposite conclusion – i.e., for the view that the dBB view should *reject* intuitive causality at the fundamental level, in favour of a symmetric picture. Goldstein and Tumulka [8] have offered a dBBB "toy model", in which microcausal retrocausality provides a Lorentz-invariant explanation of the Bell correlations. This model differs in some ways from other retrocausal proposals (e.g., [2]–[6], [9]–[18]) for reconciling these correlations with special relativity, but the underlying strategy is exactly the same: zig-zag causality, retrocausal on one arm, provides a decomposition of Bell's spacelike correlations into a product of timelike correlations.[15]

Suppose it were to turn out that abandoning intuitive causality at the fundamental level, in favour of a symmetric picture, provided a successful route to a Lorentz-invariant formulation of the dBB theory; and that we were convinced that this was the only way to make the theory Lorentz-invariant. We would then have a basis for an analogue of the argument of §3.2, within the dBB framework, in which Lorentz-invariance played the role of discreteness: if Nature is constrained to be Lorentz-invariant, She simply does not have the option of absorbing all counterfactual changes of σ_R in the future, but must allow Rena a degree of output-independent control of the past.[16]

4.6 Summary

To put the second, fourth and fifth options in perspective, it is worth noting that the relative merits of the views of QM in question – e.g., instrumentalist views, for option (2), the Everett view, for option (4), or the dBB theory, for option (5) – depend on the demerits of alternative approaches. In particular, they depend on the issue of the viability of the HV program, in the "just the particles" sense – views which combine the HV program with an epistemic view of the quantum state.

[14] As we noted earlier, avoiding retrocausality, while allowing Lena the degree of control the experimental results require, requires that Nature behave as a perfect Demon from the future, but at best as a very imperfect Demon from the past. This asymmetry would be easy to explain if we could simply *assume* intuitive causality, but it is highly puzzling if our task is to *justify* such an assumption, in the case in question.

[15] The main difference is that in the proposal in [8], the zig-zag goes initially via the future, rather than initially via the past (see [8], Figure 4, p. 563).

[16] For a friend of retrocausality, it would be an enormously satisfying result if two of the great lessons of Einstein's *annus mirabilis,* the quantisation of light and Lorentz-invariance, were to converge in this way, in support of a realist view of the quantum world.

The present result contributes to clarifying this issue, in the following sense. Bell's Theorem and other No Hidden Variable results rely on the assumption that HVs are independent of future measurement settings – an assumption with considerable intuitive appeal, against the background of the one-way causality familiar in ordinary life. However, the present argument shows that within the framework to which such a HV program is committed – a framework in which discreteness is *not* offset by non-epistemic continuity at the level of the state function – a blanket prohibition on retrocausality is incompatible with time-symmetry, in a manner specific to the QM case. This may provide some new justification for re-examining the assumption in question, and for exploring HV approaches that relax it. The photon polarization experiment discussed in §3.2 may well provide a useful model for investigating these questions, under the assumptions of time-symmetry and discrete outputs.[17]

Acknowledgements

The ideas in this paper owe a great deal to Ken Wharton, having emerged in discussion concerning related issues for our joint paper with Peter Evans [7]. I am also very grateful for comments from Richard Healey and Owen Maroney; and for research support from the Australian Research Council and the University of Sydney.

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[17] See [7] for further relevant discussion of this case, developed by means of an analogy with a photon polarization version of the EPR-Bohm experiment.

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