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Is Quantum Mechanics Non-Local? *

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Abstract

A recent proof, couched in the symbolic language of modal logic, shows that a well-defined formulation of the question posed in the title is answered affirmatively. In a paper with the same title Unruh has tried in various ways to translate the symbolic proof into normal prose, and has claimed that the proof must fail in some way or another. A correct translation is given here, and it is explained why the difficulties encountered by Unruh do not actually arise.

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One of the great lessons of quantum theory is that utmost caution must be exercised in reasoning about hypothetical outcomes of unperformed experiments. Yet Bohr [1] did not challenge the argument of Einstein, Podolsky, and Rosen [2] on the grounds that it was based on the simultaneous consideration of mutually exclusive possibilities. Rather he challenged the underlying EPR presumption that an experiment performed locally on one system would occur "without in any way disturbing " a faraway system. Bohr's own ideas rested heavily on the idea that experimenters could freely choose between alternative possible measurements, and the core of his answer to EPR was that although *"... there is in a case like that just considered no question of a mechanical influence of the system under investigation during the last critical stage of the measuring procedure."*..."there is essentially the question of *an influence of the very conditions which define the possible types of predictions about future behavior of the system."*

The adequacy of Bohr's answer, and the nature of his intermediate position on the question of these influences, has been much debated. The issue is of fundamental importance, because it concerns the nature of the causal structure of quantum theory, and its compatibility with the idea, drawn from the theory of relativity, that no influence of any kind can act backward in time in any frame.

To obtain rigorous results in this realm it is useful to formulate arguments within a formal logic, where each separate statement can be stated precisely, and the rules of inference connecting them are exactly spelled out. This was done in reference [3] where a logical contradiction was shown to arise from a combination of explicitlty stated assumptions. One of these assumptions was a locality (no-faster-than-light-influence) condition LOC1, which expresses Bohr's "no mechanical influence" condition. It states that if an experiment L2 is actually performed in a spacetime region L, and an experiment R2 is actually performed in a faraway region R that lies later in time than L (in some frame), and if an outcome c appears to the observers stationed in the earlier region L, then that same result c would have appeared to the observers in L in the alternative possible case in which nothing is changed except for the later-in-time free choice by the experimenter in R and the consequences of this change: LOC1 asserts that the later free choice in R has no effect on the outcome that appeared earlier to the observers stationed in region L.

The argument in reference [3], stated here in words, rather than the symbols of modal logic, starts as follows:

Suppose the actual situation is such that L2 and R2 are performed and the outcome g appears to the observers in R. Then a prediction of quantum theory, in the Hardy case under consideration in [3], entails that the outcome appearing to the observers in L must be c, in this actual situation. But according to LOC1 this actual outcome c appearing to the observers in L would not be disturbed if the later free choice in R were to perform R1 instead of R2: the actual outcome appearing to the observers in L would remain c. But then if the laws of quantum theory are assumed to hold not only in the single unique world that is actually created by our free choices but also in the alternative possible worlds that would be created if our alternative free choices had been different, then another prediction of quantum theory in this Hardy case entails that the outcome appearing to the observers in R, in this alternative possible situation (in which R1 is performed instead of R2) must be f.

This result is summarized in line 5 of my proof, which in prose reads:

LINE 5: If L2 is performed then SR is true,

where SR is the statement:

SR: "If R2 is performed in R and outcome g appears to the observers in R, then if R1, instead of R2, had been performed in R the outcome f would have appeared to the observers in R."

The form of this claim in line 5 is the same as a typical claim in classical mechanics: if the result of a certain measurement 1 is, say, g, then the deterministic laws of physics may allow one to deduce that if some alternative possible measurement 2 had been performed, instead of 1, then the result of that measurement 2 would necessarily have been f: knowledge of what happens in an actual experimental situation may, with the help of theory, allow one to infer what would have happened if one had performed, instead, a different experiment.

Note that the assumptions in line 5 pertaining to region L do not include the condition that outcome c appears to the observers in L: that condition is implied by the predictions of quantum theory and the explicitly stated conditions, namely that L2 and R2 are actually performed, and that outcome g appears to the observers in R.

This prose description is clear and direct, and it conforms to the meanings ascribed to the statements in my proof by the rules modal logic. This logic has been developed by philosophers and logicians for dealing with statements of the sort occurring here. Of course, that logic was designed to formalize normal rational thinking, and it may therefore incorporate philosophical prejudices drawn from the prevailing classical conception of the nature of reality. Still, Bohr strongly supported the idea that no non-classical-type of logic or reasoning is needed to deal with our descriptions at the level of possible experimental set-ups, and our observations of their outcomes. No other kind of description enters into my argument.

Unruh [4] has set forth an array of different interpretations of practically every statement in my proof, and has encountered all sorts of difficulties.

Of the interpretations of LOC1 offered by Unruh, the one closest to the one occurring in my proof is the one he describes first: "On face value this is just the unexceptional statement that if L2 is measured to have value c then the truth of having obtained that value is independent of what is (or will be) measured at R". My statement is only slightly different: "This is just the unexceptional statement that if L2 is measured and the outcome appearing to the observers in L is c, then this latter fact is independent of which measurement will later be performed in R: the later free choice by the experimenter in R does not disturb what was observed earlier by the observers in region L."

Unruh claims that "this meaning of LOC1 is insufficient to derive his [Stapp's] conclusion, since it demands that L2 had actually been measured and had the given outcome. It ties the meaning of this locality condition to the actuality of the measurement and its outcome. This does not allow counterfactual replacement of L2, since the truth of this statement is, under this interpretation, tied to the truth of the measurement of attribute L2 actually having been carried out in L, and having obtained that specified outcome." [I have replaced by L2 some apparent misprints]

To evaluate this objection we must turn to the second locality condition, LOC2, and its application, for that is where the condition L2 is relaxed.

LOC2 is connected to line 5, which says that if L2 is performed then statement SR is true.

Suppose the experiment L2 is performed in a spacetime region that lies much later in time (in some frame) than all points in the region R in which all of the possible events referred to by SR lie. And suppose the later choice between L1 and L2 is really free: i.e., that this choice is independent of everything that happens earlier.

Then the demand that there be no backward-in-time influence of any kind requires that SR cannot be necessarily true if the later free choice is L2, but be untrue if the later free choice is L1: such a difference would constitute *some sort* of backward-in-time influence.

LOC2 is, accordingly, the assertion that if SR is true under condition L2, then it is also true if L1, instead of L2, is performed in L.

Of course, the *proof* that SR is true under condition L2 depends upon the fact that L2 is performed, and that *proof* certainly fails if L2 is not performed. But LOC2 does not say that the *proof* of SR carries over to the case in which L1, instead of L2, is performed in L. It asserts only the *truth* of SR does not depend on a free choice that is made at a time that is later than the times of all the possible events whose occurrences or non-occurrences under various conditions specified in R determine, by definition, the truth of SR.

What does Unruh say about LOC2?

He says: "If it were true that one could deduce solely from the fact that a measurement had been made at L that some relation on the right must hold, then I would agree that this requirement [LOC2] would be reasonable."

Well, one needs, of course, the other assumptions, including LOC1. But, given those other assumptions, which I have specified, one can deduce SR "solely" from the assumption that L2 is performed: one does not need to assume that the outcome appearing to the observers stationed in L is c. So Unruh's statement appears to confirm that LOC2 is a valid expression of the condition that there be no influence backward in time.

But then he immediately says: "However, if the truth of the relation on the right hand side depended not only on which measurement had been made [I would say "will be made"] on the left, but also on the actual value obtained on the left, then no such locality condition would obtain."

This muddies the waters, for it seems to contradict what he just said. How is this conflict resolved?

In logic one distinguishes between "proof", "truth", and "meaning". Unruh's arguments blur these distinctions. He speaks of the dependence of the *truth* of SR upon actual values obtained on the left. What is true is that the *proof* of SR depends on the actual value c that appears on the left. But it does not follow that the *truth* of SR depends on what happens later in region L. The truth of SR depends, by definition, on the occurrence or non-occurrence of possible events in the earlier region R, under various conditions freely chosen in R. LOC2 is the assertion that the free choice made later by the experimenter in L leaves undisturbed an existing pattern in those earlier possible events in R.

What about Unruh's earlier claim that "this meaning of LOC1, is insufficient to derive his [Stapp's] conclusion, since it demands that L2 had actually been measured and had the given outcome. It ties the meaning of this locality condition to the actuality of the measurement and its outcome. This does not allow counterfactual replacement of L2, since the truth of this statement is, under this interpretation, tied to the truth of the measurement of attribute L2 actually having been carried out in L, and having obtained that specified outcome."

It is of course essential, in following a logical argument, to proceed step-by-step in a logical progression that leads from the assumptions to the conclusions, rather than collapsing the steps to a single unjustified leap. In my proof the assumption LOC1 is used to get line 5. In that application of LOC1 the experiment performed in region L is fixed to be the actually performed experiment L2. And the premise of SR, together with a prediction of quantum theory, allows one to conclude that the outcome actually observed by the observers in L is the outcome c. So all the conditions for the applicability of LOC1 are satisfied. LOC1 is not used thereafter.

The answer, therefore, to Unruh's claim about the insufficiency of LOC1 is that LOC1 is used only under conditions where its use is justified, and in particular only under the condition that L2 is performed in L.

Unruh advances several other arguments that I should also address. He suggests that perhaps LOC1 means that "if one is somehow able to infer that L2 has value c then it remains true that L2 has value c under replacement of R2 with R1 even if the outcome of the measurement R2 was crucial in drawing the inference that L2 has value c." He says that: "This interpretation of LOC1 is. I would argue, a form of realism, in that it claims that the value to be ascribed to L2 is independent of the evidence used to determine that value."

This argument confounds several separate steps in my argument. LOC1 asserts merely that if L2 and R2 are performed in L and R respectively, where L is earlier than R in some frame, and if outcome c appears to the observers stationed in L, then that same result c would appear to these observers in L if everything were kept exactly the same except for the later-in-time free choice by the experimenter in R, and the consequences of that change. In the actual situation specified by the three conditions L2 and R2 and g a result from quantum theory entails that the outcome c appears to the observers in L. Given this fact, one can use LOC1 to deduce what "would happen" in L in the hypothetical situation in which this factual situation is changed solely by a change in the free choice in R and the consequences of that change. According to LOC1 this change in R would not disturb the actual outcome that appears to the observers stationed in the earlier region L: the observers in the earlier region L would continue to observe outcome c.

As in most logical arguments it is important to follow the steps in the proof. In this case the "evidence" for the fact that the actual result in L is c, lies in the fact that the actual situation under consideration is one in which L2 and R2 are performed, and the outcome appearing to the observers in R is g, combined with the knowledge provided by quantum theory that under these conditions the outcome appearing to the observers in L is c.

Of course, one of the consequences of changing the free choice made in R from R2 to R1 is that under these altered conditions the outcome appearing to the observers *in R* would be different from what it actually is. But LOC1 asserts that what has already been observed by the observers stationed in the earlier region L will not be changed by this change in the later free choice made in R: the present actual evidence of one's senses does not depend on what some experimenter will freely choose to do tomorrow, as it might well do if that later free choice could effect prior events.

Unruh considers my line 4, and says: "The claim is that this arises solely by logic out of the substitution of (2) and (3) into (1). However, it is now clear that the meanings ascribed to LOC1 and to the statements of the logical calculus are crucial."

It certainly is clear that meanings ascribed to LOC1 and the statements of the logical calculus are crucial. I have spelled out here in prose what these meanings are, and how they enter into my proof. Unruh proposes some other meaning, which he formalizes in his Eq. 14.

Whatever that equation means, it definitely does not conform to the rules of modal logic. Certainly, one cannot say, as Eq. 14 does, that if R1 is performed instead of R2 then R2 is performed. And Unruh's claim that the final inference, namely that (L2 and c and R2 and f) implies (L2 and R1 and f) "is no longer true" certainly makes his logic incompatible with modal logic, and with classical logic as well.

Unruh goes on to restate his objections in various other ways, But I believe I have already explained how my proof rationally evades all of the difficulties he encountered.

References

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[4] W. Unruh, Phys. Rev. A, to appear. (quant-ph/9710032).