Is retrocausal quantum mechanics consistent with special relativity?

Shan Gao
Research Center for Philosophy of Science and Technology,
Shanxi University, Taiyuan 030006, P. R. China
E-mail: gaoshan2017@sxu.edu.cn.

June 7, 2022

Abstract

Retrocausal quantum mechanics (RQM) provides a local causal explanation of Bell correlations. It is widely thought that RQM is consistent with special relativity. In this paper, I point out that this view is not wholly right. It is argued that RQM violates the Lorentz invariance of the temporal relation between cause and effect for certain spacelike separated events in Bell-type experiments.

It has been debated whether quantum theory and special relativity are compatible. In 1964, based on the Einstein-Podolsky-Rosen (EPR) argument (Einstein et al, 1935), Bell derived an important result that was later called Bell's theorem (Bell, 1964). It states that certain predictions of quantum mechanics cannot be accounted for by a local theory, and thus strongly suggests that quantum mechanics and special relativity are incompatible. However, Bell's theorem is also based on certain supplementary assumptions, one of which is that there is no retrocausality in quantum mechanics.

It has been demonstrated that by rejecting this supplementary assumption, the Bell correlations can be given a local causal account (Price 1994, 1996, 2008; Corry, 2015; Sen, 2019; Friederich and Evans, 2019; Wharton and Argaman, 2020). It is widely thought that the retrocausal approaches to quantum mechanics or retrocausal quantum mechanics (RQM) is consistent with special relativity. In this paper, I point out that this view is not wholly right. It is argued that RQM violates the Lorentz invariance of the temporal relation between cause and effect for certain spacelike separated events in Bell-type experiments.

In special relativity, it is usually thought that the temporal relation between cause and effect should be Lorentz invariant. This means that if a cause precedes its effect in one Lorentz frame, then this will hold true in all other Lorentz frames. For normal causal processes, causes will precede effects in every Lorentz frame. In RQM, there are also retrocausal processes. For these processes, effects will precede causes in every Lorentz frame, and thus they also satify the Lorentz invariance of the temporal relation between cause and effect (LITRCE in brief).[1] Now the question is: when a retrocausal process and a normal causal process in RQM are combined to explain the Bell correlations, does the combined process still satisfy LITRCE?

Consider a usual Bell-type experiment. There are two observers Alice and Bob who are in their separate laboratories and share an EPR pair of spin 1/2 particles in the spin singlet state:

$$\frac{1}{\sqrt{2}}(|\uparrow\rangle_1 |\downarrow\rangle_2 - |\downarrow\rangle_1 |\uparrow\rangle_2). \tag{1}$$

Alice measures the spin of particle 1 at angle a, and Bob measures the spin of particle 2 at angle b. These two measurements can be spacelike separation. Each measurement result is $+1$ or -1, corresponding to spin up or spin down. Then we can calculate the probabilistic correlation function $E(a,b)$ for Alice's and Bob's measurement results according to the Born rule, which is $E(a,b) = -cos(a-b)$.

Here is an explanation of this Bell-type experiment provided by RQM. The core assumption is that in such Bell-type experiments the measurement settings as a cause (in the future) can affect the hidden-variable distribution during preparation (in the past) by a retrocausal mechanism. Concretely speaking, in the above experiment, Alice's measurement setting a and Bob's measurement setting b retrocausally affect the values of spin of particles 1 and 2 along these directions (as hidden variables of the theory) during preparation, so that these values are correlated in a way to be able to explain the Bell correlations between Alice's and Bob's measurement results which are assumed to directly reflect these values of spin.

A key feature of RQM is that no matter what retrocausal mechanism the theory assumes, there are causal influences between spacelike separated events in this Bell-type experiment. For example, Alice's measurement and Bob's measurement are spacelike separation, and Alice's measurement setting affects Bob's measurement result; Alice's measurement setting first retrocausally affects the value of spin of particle 2 (as well as the value of spin of particle 1), and then the spin of particles 2 determines Bob's measurement result. Suppose that in the laboratory frame (in which Alice's and Bob's laboratories are at rest) Alice's measurement and Bob's measurement

[1] Note that the Lorentz invariance of the relation of temporal precedence has been discussed by Myrvold et al (2019). Temporal precedence means that causes always preceding their effects temporally. Here LITRCE can be regarded as an extension to this principle for normal causal processes, and it may apply to both normal causal processes and retrocausal processes.

occur at the same time, and the causal influence of Alice's measurement upon Bob's result is effectively instantaneous (via the zig-zag in the past). Then in another Lorentz frame, Alice's measurement (as a cause) may occur earlier or later than Bob's result (as an effect) due to Lorentz boosts. This means that LITRCE has been violated.

In the de Broglie-Bohm theory and collapse theories, there are causal influences between spacelike separated events in Bell-type experiments, and it is a known result that these theories violate LITRCE. For example, in collapse theories, the measurement on one particle affects the other entangled particle instantaneously in Bell-type experiments in a preferred Lorentz frame. Now in RQM there are also causal influences between spacelike separated events in Bell-type experiments. The difference lies only in that the spacelike causation is direct, via action at a distance in the de Broglie-Bohm theory and collapse theories, while the spacelike causation is indirect, via the zig-zag in the past, in RQM. Then, it will be not surprising that RQM also violates LITRCE.

Here it is worth emphasizing again that the retrocausal processes in RQM alone do not violate LITRCE, and retrocausality or rejecting the relation of temporal precedence is not an issue either. But when a retrocausal process and a normal causal process are combined to explain the Bell correlations, there will be spacelike causation or causal influences between spacelike separated events. It is the existence of such influences that leads to the violation of LITRCE.[2]

Usually in a theory where LITRCE is violated, one can define a preferred Lorentz frame. For instance, in collapse theories, the preferred Lorentz frame can be defined as the frame in which the collapse of the wave function (e.g. the spin singlet state of the two particles in Bell-type experiments) is simultaneous in different regions of space. Similarly, the preferred Lorentz frame in RQM may be defined as the frame in which the measurement on one particle affects the other entangled particle instantaneously (via the zig-zag in the past) in Bell-type experiments. In other frames, the measurement on one particle will affect the other entangled particle later or earlier. Certainly, a more fundamental definition of the preferred Lorentz frame in RQM must be ultimately related to the underlying mechanism of the theory to explain Bell correlations.

A possible response to the above result is to accept the conclusion that

[2]Note that if there are no causal influences between spacelike separated events, then the existence of these events is consistent with special relativity, and they do not violate LITRCE either. This is the common case in classical mechanics. In this case, the temporal order of spacelike separated events is not Lorentz invariant, and it has no physical significance. By comparison, if there is a causal connection between two spacelike separated events as in RQM, then the temporal order of these events will have physical significance relating to causation. For example, it is required by special relativity that causes should precede effects for normal causal processes in every Lorentz frame. Thus whether a theory satisfies LITRCE in this case will be an important question.

the temporal relation between cause and effect is a frame-dependent matter in certain spacelike cases in RQM and argue that this is not a problem for the theory. Indeed, given that RQM has already rejected the principle that causes need to precede their effects, it seems understandable that the temporal relation between cause and effect may be not Lorentz invariant in certain cases. In this sense, RQM is not in same tension with special relativity as the de Broglie-Bohm theory and collapse theories.

To sum up, I have argued that RQM is not consistent with special relativity in certain aspects. In RQM, there are spacelike causation or causal influences between spacelike separated events in Bell-type experiments, and the existence of such influences will lead to the violation of the Lorentz invariance of the temporal relation between cause and effect.

References

[1] Einstein, A., B. Podolsky, and N. Rosen (1935). Can quantum-mechanical description of physical reality be considered complete? Physical Review 47, 777.

[2] Bell, J. S. (1964). On the Einstein-Podolsky-Rosen paradox. Physics, 1, 195-200.

[3] Corry, R. (2015). Retrocausal models for EPR. Studies in History and Philosophy of Modern Physics 49, 1-9.

[4] Friederich, S. and P. W. Evans (2019). Retrocausality in Quantum Mechanics, The Stanford Encyclopedia of Philosophy (Summer 2019 Edition), Edward N. Zalta (ed.), https://plato.stanford.edu/archives/sum2019/entries/qm-retrocausality/.

[5] Myrvold, W., M. Genovese and A. Shimony (2019). Bell's theorem. The Stanford Encyclopedia of Philosophy (Spring 2019 Edition), Edward N. Zalta (ed.), https://plato.stanford.edu/archives/spr2019/entries/bell-theorem/.

[6] Price, H. (1994). A Neglected Route to Realism about Quantum Mechanics, Mind, 103, 303-336.

[7] Price, H. (1996). Time's Arrow and Archimedes' Point: New Directions for the Physics of Time. Oxford: Oxford University Press.

[8] Price, H. (2008). Toy models for retrocausality. Studies in History and Philosophy of Modern Physics, 39, 752-761.

[9] Sen, I. (2019). A Local ψ-Epistemic Retrocausal Hidden-Variable Model of Bell Correlations with Wavefunctions in Physical Space. Foundations of Physics 49, 83.

[10] Wharton, K. B. and Argaman, N. (2020). Colloquium: Bell's theorem and locally mediated reformulations of quantum mechanics. Reviews of Modern Physics, 92, 021002.