Unitary quantum theory is incompatible with special relativity

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November 6, 2018

Abstract

It is shown that the combination of unitary quantum theory and special relativity may lead to a contradiction when considering the EPR correlations in different inertial frames in a Gedankenexperiment. This result seems to imply that either unitary quantum theory is wrong or if unitary quantum theory is right then there must exist a preferred Lorentz frame.

It has been debated whether quantum mechanics and special relativity are compatible. In this paper, I will give a simple proof of the incompatibility between unitary quantum theory and special relativity based on an analysis of the EPR correlations in different inertial frames.

Consider a Gedankenexperiment in which there are two observers Alice and Bob and a superobserver who can undo the measurements of Alice and Bob (the existence of such a superobserver is permitted by unitary quantum theory). Alice and Bob are in their separate laboratories and share an EPR pair of spin-1/2 particles in the spin singlet state:

$$\frac{1}{\sqrt{2}}(|up\rangle_1 |down\rangle_2 + |down\rangle_1 |up\rangle_2). \quad (1)$$

Alice measures the spin of particle 1 at angle a, and Bob measures the spin of particle 2 at angle b. 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 quantum mechanics.

Now suppose in Alice's lab frame, Alice first measures the spin of particle 1 at angle a and obtains her result in her laboratory, then Bob measures the spin of particle 2 at angle b and obtains his result in his laboratory, and finally the superobserver, who is near and at rest relative to Alice's laboratory, undoes Alice's measurement (see [1-7]). When the superobserver's reset measurement is spacelike separated from Bob's measurement, and Alice's and Bob's laboratories are in relative motion, the following time order of events in Bob's lab frame is permitted by special relativity. In Bob's frame, Alice first measures the spin of particle 1 at angle a and obtains her result, then the superobserver undoes Alice's measurement, and finally Bob measures the spin of particle 2 at angle b and obtains his result.[1]

Then we can calculate the correlation function $E(a, b)$ in Alice's and Bob's frames. In Alice's frame, as in the usual EPR-Bohm experiment, we have $E(a, b) = -cos(a - b)$, and especially, when $a = b$, we have $E(a, b) = -1$. In Bob's frame, since after the superobserver's reset measurement the states of Alice and the particles are the same as their initial states, the result of Bob's measurement has no correlation with the result of Alice's measurement. Then we have $E(a, b) = 0$ for any a, b. On the other hand, since the expectation values of the same joint measurements observed in two inertial frames should be the same, the correlation function $E(a, b)$ is invariant under changes of frame. Thus we have derived a contradiction.

The contradiction can also be seen from an analysis of a single measurement result. Consider the EPR anti-correlation case of $a = b$. In Alice's frame, when the result of Alice's measurement is $+1$, the result of Bob's measurement must be -1 with certainty. But in Bob's frame, when the result of Alice's measurement is $+1$, the result of Bob's measurement may be $+1$ with probability $1/2$. Note that the results of the same measurement observed in two inertial frames should be the same. Thus we also have a contradiction.

It can be seen that the above contradiction results from the combination of unitary quantum theory and special relativity. Unitary quantum theory permits the existence of the superobserver's reset measurement, and special relativity permits the change of time order of events in different frames. It is these two elements in combination that lead to the contradiction in the above Gedankenexperiment.

Avoiding the above contradiction requires that either unitary quantum theory or special relativity is wrong. If unitary quantum theory is wrong, e.g. in collapse theories, then the superobserver who can undo a measurement will not exist, and the above contradiction can be avoided. On the other hand, if unitary quantum theory is right, then special relativity must be violated. Concretely speaking, in a unitary quantum theory there must exist a preferred Lorentz frame, in which the time order of events is real and

[1]Note that when the distance between Alice's and Bob's laboratories is very large and the duration between the superobserver's reset measurement and Bob's measurement is very short, the relative velocity of Alice's and Bob's laboratories may be close to zero.

the correlation functions derived from it are also real, while in other frames the time order of events is apparent and the true correlation functions are the same as the correlation functions in the preferred Lorentz frame.[2]

To sum up, I have argued that the combination of unitary quantum theory and special relativity may lead to a contradiction when considering the EPR correlations in different inertial frames. This result seems to imply that either unitary quantum theory is wrong or if unitary quantum theory is right then there must exist a preferred Lorentz frame.

Acknowledgments

I wish to thank Richard Healey for helpful discussion at the online Workshop on Wigner's Friend 2018, which was hosted by International Journal of Quantum Foundations. This work is supported by the National Social Science Foundation of China (Grant No. 16BZX021).

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[2] It seems that in order to explain the existence of the preferred Lorentz frame, there must also exist underlying nonlocal processes induced by measurements. This possible implication needs to be further investigated.