“Perception” at a distance in EPR-Bohm experiments with reversible measurements

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Abstract

According to the no-signaling theorem, in EPR-Bohm experiments or Bell-type experiments, one experimenter’s statistic does not depend on the other experimenter’s choice of measurement when they are spacelike separated. In this paper, I argue that this is not wholly correct. It is shown that in a EPR-Bohm experiment with reversible measurements, one experimenter’s statistic, which is in principle inaccessible, depends on the other experimenter’s choice of measurement when they are spacelike separated in a single-world unitary quantum theory. This presents the first example of “perception” at a distance at the observational level. Possible implications of this new effect such as violation of special relativity are also discussed.

1 Introduction

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 theory and special relativity are incompatible. On the other hand, it is usually thought that the EPR-Bohm experiments, unlike the Bell-type experiments, cannot be used to demonstrate the existence of nonlocal correlations that leads to potential incompatibility of quantum theory and special relativity. In this paper, I will propose a variant of the original EPR-Bohm experiment, a new EPR-Bohm experiment with reversible measurements. It is argued that this experiment can be used to demonstrate the existence of superluminal causal influence, as well as the incompatibility of certain quantum theories and special relativity such as the existence of a preferred Lorentz frame in these theories.

The rest of this paper is organized as follows. In Section 2, I propose a variant of the EPR-Bohm experiment with reversible measurements, which are permitted by a unitary quantum theory. Moreover, I argue that in this experiment one experimenter's statistic, which is in principle inaccessible, depends on the other experimenter's choice of measurement when they are spacelike separated in a single-world unitary quantum theory. This presents the first example of "perception" at a distance at the observational level. In Section 3, I discuss possible implications of this new effect of "perception" at a distance. Conclusions are given in the last section.

2 A new EPR-Bohm experiment with reversible measurements

Let's first consider a usual EPR-Bohm 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:

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

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 separated. 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 $E(a, b) = -cos(a - b)$. In particular, in the EPR anti-correlation case of $b = a$, we have $E(a, b) = -1$, which means that when Alice's result is $+1$, Bob's result is -1, and vice versa.

Now consider a variant of the above EPR-Bohm experiment. In this new experiment, there is an additional superobserver in Alice's laboratory who can reverse or undo her measurement, which is permitted by a unitary quantum theory. Moreover, the superobserver prepares an ensemble of particles 3 in Alice's laboratory, each of which is in the z-spin up state. I will consider only single-world unitary quantum theories in my following analysis.[1]

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[1] A single-world unitary quantum theory can be defined as a quantum theory in which each isolated system including a measuring device can be assigned to a wave function, and the time evolution of the wave function is always governed by the Schrödinger equation, and the result of each measurement is unique, whose probability satisfies the Born rule. Then, a single-world unitary quantum theory in principle permits that a measurement can be reversed so that the state of the measured system and the measuring device is restored. Note that there are already some discussions about Bell-type experiments with superobservers in the literature (Brukner, 2015; Frauchiger and Renner, 2016, 2018; Pusey,

First, suppose in the laboratory frame (in which Alice's and Bob's laboratories are at rest), the superobserver first entangles one particle 3 with particle 1 by a local interaction to form the following state:

$$\frac{1}{\sqrt{2}}(|{\uparrow_z}\rangle_1 |{\downarrow_z}\rangle_2 |{\uparrow_z}\rangle_3 - |{\downarrow_z}\rangle_1 |{\uparrow_z}\rangle_2 |{\downarrow_z}\rangle_3), \tag{2}$$

where the spin of particle 3 and the spin of particle 2 are anti-correlated in the z direction. Then Alice measures the spin of particle 3 at angle z and obtains her result, and then the superobserver disentangles particle 3 from particle 1 and discards it and reverse Alice's measurement. Then the superobserver entangles another particle 3 with particle 1, and Alice measures again the spin of particle 3 at angle z and obtains her second result, and then particle 3 is disentangled and discarded and Alice's second measurement is reversed, and this process repeats a large number of times. Each of Alice's measurements and the reverse operations can be formulated as follows:

$$\begin{aligned} & U_A^{3\dagger} U_A^3 \frac{1}{\sqrt{2}}(|{\uparrow_z}\rangle_1 |{\downarrow_z}\rangle_2 |{\uparrow_z}\rangle_3 - |{\downarrow_z}\rangle_1 |{\uparrow_z}\rangle_2 |{\downarrow_z}\rangle_3) |ready\rangle_A |ready\rangle_B \\ = \; & U_A^{3\dagger} \frac{1}{\sqrt{2}}(|{\uparrow_z}\rangle_1 |{\downarrow_z}\rangle_2 |{\uparrow_z}\rangle_3 |{\uparrow_z}\rangle_A - |{\downarrow_z}\rangle_1 |{\uparrow_z}\rangle_2 |{\downarrow_z}\rangle_3 |{\downarrow_z}\rangle_A) |ready\rangle_B \\ = \; & \frac{1}{\sqrt{2}}(|{\uparrow_z}\rangle_1 |{\downarrow_z}\rangle_2 |{\uparrow_z}\rangle_3 - |{\downarrow_z}\rangle_1 |{\uparrow_z}\rangle_2 |{\downarrow_z}\rangle_3) |ready\rangle_A |ready\rangle_B \end{aligned} \tag{3}$$

In this case, according to the Born rule, the probability distribution of Alice's results is $P(+1) = 1/2$ and $P(-1) = 1/2$. Then, after a large number of repeated-and-erased measurements, Alice will obtain two different results, spin up and spin down, with roughly equal frequency.[2]

Next, suppose in the laboratory frame, Bob measures the spin of particle 2 at angle z and obtains his result, then the superobserver entangles one particle 3 with particle 1 by the same local interaction as above to form the

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2016; Healey, 2018; Leegwater, 2018; Lazarovici and Hubert, 2018).

[2] A careful reader may notice that there is a simpler version of this experiment without using an ensemble of particles 3. In this simpler experiment, in the laboratory frame, Alice first measures the spin of particle 1 at angle z and obtains her result, then Alice's measurement is reversed by the superobserver, and then Alice measures again the spin of particle 1 at angle z and obtains her second result, and then Alice's second measurement is reversed, and this process repeats a large number of times (Gao, 2018). However, in this experiment, the probability distribution of Alice's results does not necessarily satisfy the Born rule. For example, in a deterministic hidden-variable theory such as the de Broglie-Bohm theory, when the superobserver's reverse operation is an exact time-reversal, it will restore the values of all hidden variables such as the positions of all Bohmian particles to their initial values, and thus the results of Alice's measurements will be all the same. In this case, we cannot derive the effect of "perception" at a distance.

state:

$$\frac{1}{\sqrt{2}}(\left|\uparrow_z\right\rangle_1\left|\downarrow_z\right\rangle_2\left|\downarrow_z\right\rangle_B\left|\uparrow_z\right\rangle_3-\left|\downarrow_z\right\rangle_1\left|\uparrow_z\right\rangle_2\left|\uparrow_z\right\rangle_B\left|\downarrow_z\right\rangle_3). \tag{4}$$

Then Alice measures the spin of particle 3 at angle z and obtains her result, and then particle 3 is disentangled and discarded and Alice's measurement is reversed, and then the superobserver entangles another particle 3 with particle 1, and Alice measures again the spin of particle 3 at angle z and obtains her second result, and this process repeats a large number of times. Each of Alice's measurements and the reverse operations after Bob's measurement can be formulated as follows:

$$\begin{aligned}
& U_A^{3\dagger}U_A^3\frac{1}{\sqrt{2}}(\left|\uparrow_z\right\rangle_1\left|\downarrow_z\right\rangle_2\left|\downarrow_z\right\rangle_B\left|\uparrow_z\right\rangle_3-\left|\downarrow_z\right\rangle_1\left|\uparrow_z\right\rangle_2\left|\uparrow_z\right\rangle_B\left|\downarrow_z\right\rangle_3)\left|ready\right\rangle_A \\
= \; & U_A^{3\dagger}\frac{1}{\sqrt{2}}(\left|\uparrow_z\right\rangle_1\left|\downarrow_z\right\rangle_2\left|\downarrow_z\right\rangle_B\left|\uparrow_z\right\rangle_3\left|\uparrow_z\right\rangle_A-\left|\downarrow_z\right\rangle_1\left|\uparrow_z\right\rangle_2\left|\uparrow_z\right\rangle_B\left|\downarrow_z\right\rangle_3\left|\downarrow_z\right\rangle_A) \\
= \; & \frac{1}{\sqrt{2}}(\left|\uparrow_z\right\rangle_1\left|\downarrow_z\right\rangle_2\left|\downarrow_z\right\rangle_B\left|\uparrow_z\right\rangle_3-\left|\downarrow_z\right\rangle_1\left|\uparrow_z\right\rangle_2\left|\uparrow_z\right\rangle_B\left|\downarrow_z\right\rangle_3)\left|ready\right\rangle_A \qquad (5)
\end{aligned}$$

In this case, according to the Born rule, each of Alice's results will be anti-correlated with Bob's result, and thus the probability distribution of Alice's results is either $P(+1) = 0$ and $P(-1) = 1$ (when Bob's result is $+1$) or $P(+1) = 1$ and $P(-1) = 0$ (when Bob's result is -1).[3] Then, after a large number of repeated-and-erased measurements, Alice will always obtain the same result, either spin up or spin down.

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[3] Note that quantum mechanics predicts and experiments also show that Alice's results are anti-correlated with Bob's result even if their measurements are spacelike separated (cf. Healey, 2021).

Measurements	1	2	3	4	5	6	...
Results	$+1$	-1	-1	$+1$	-1	$+1$	...

Table 1: Alice's results when Bob does not measure

Measurements	1	2	3	4	5	6	...
Results (when B = $+1$)	-1	-1	-1	-1	-1	-1	...

Measurements	1	2	3	4	5	6	...
Results (when B = -1)	$+1$	$+1$	$+1$	$+1$	$+1$	$+1$	...

Table 2: Alice's results when Bob measures

Note that since the results of measurements are objective physical fact (relative to the measurer at least), the statistic of Alice's measurement results exists objectively. However, since all of Alice's measurement results are erased by the superobserver at the end of these experiments, the statistic of Alice's results can only be calculated from a theory, and it cannot be found by experiments or it is not epistemically accessible to any experimenter in principle. This is consistent with the no-signaling theorem; otherwise Bob can send a superluminal signal to Alice by measuring the spin of particle 2, and Alice can decode the signal by looking at the statistic of her measurement results.

3 "Perception" at a distance and its possible implications

The above analysis shows that in the suggested EPR-Bohm experiment with reversible measurements, the statistic of the results of Alice's repeated measurements depends on Bob's measurement choice when they are spacelike separated. When Bob does not make a measurement, Alice will obtain two different results, spin up and spin down, with roughly equal frequency, while when Bob makes a measurement (before Alice's measurements), Alice will always obtain the same result, either spin up or spin down. Thus Alice's measuring device can "perceive" Bob's measurement choice at a distance! This effect of "perception" at a distance at the observational level is predicted by a single-world unitary quantum theory (SUQT in brief).[4] The effect can also be demonstrated by other less simple experiments such as Bell-type experiments.

It can be seen that the effect of "perception" at a distance violates special relativity, since it depends on distant simultaneity or the temporal order of spacelike separated events, which is not Lorentz invariant.[5] This also means that there must exist a preferred Lorentz frame in a SUQT. The preferred Lorentz frame can be defined as the Lorentz frame in which the probability of Alice's result is instantaneouly determined by Bob's measurement choice or "perception" at a distance requires no time. In this preferred Lorentz frame, the predictions of the theory are always true, while in other Lorentz

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[4] It seems that the statistic of Alice's results cannot be properly defined in many worlds due to world merging resulting from reversed measurements. I will not discuss the many-worlds interpretation of quantum mechanics in this paper.

[5] Note again that although Alice cannot remember or report the statistic of her results, this only means an impossibility of testing certain predictions of a theory at the empirical level, while what I consider here is whether the predictions of two theories are compatible. After all, the statistic of the results of Alice's repeated-and-erased measurements in each Lorentz frame can be properly defined and also precisely predicted by a SUQT and special relativity.

frames the predictions of the theory are not always true.[6]

It is widely thought that there are single-world quantum theories which can explain the Bell inequality-violating correlations predicted by quantum mechanics and are also compatible with special relativity. Examples include relational quantum theories, such as relational quantum mechanics (Rovelli, 1996; Smerlak and Rovelli, 2017) and perspectivalism (Dieks, 2018, 2019), retrocausal theories (Price, 1996; Corry, 2015; Sen, 2019; Wharton and Argaman, 2020) and superdeterminism ('t Hooft, 2016). This is because there are supplementary assumptions besides the locality assumption in the proof of Bell's theorem, such as the measurement independence assumption (Myrvold et al, 2019), while these theories drop one of these supplementary assumptions.

The above analysis of the incompatibility between SUQTs and special relativity does not rely on the supplementary measurement independence assumption of Bell's theorem, which assumes the independence of the complete state of the systems and the experimental settings. The reason is that the above analysis does not concern the complete state of the systems, but only concerns the measurement results. Thus, if a single-world quantum theory belongs to SUQTs, then it will be incompatible with special relativity according to the above analysis.

A typical example of SUQTs is the de Broglie-Bohm theory and the modal interpretations. In the de Broglie-Bohm theory, the velocity of a particle depends on the positions of any other particles it is entangled with, and thus the theory can readily explain the effect of "perception" at a distance. It has been shown that in the de Broglie-Bohm theory, the joint distributions given by the Born rule for position measurements cannot in general agree with the distributions of the actual Bohmian particle positions in all Lorentz frames (Berndl et al, 1996). Moreover, it is shown that in the modal interpretations, special relativity is violated and a preferred Lorentz frame exists at the assumed ontological level (Myrvold, 2002).[7] By comparison, the above analysis is based on the new effect of "perception" at a distance and it provides a more general proof of the existence of a preferred Lorentz frame in hidden-variable theories by considering only measurement results.

Another example of SUQTs is relational quantum theories. These theories assume that measurement results may be different relative to different physical systems (Rovelli, 1996; Smerlak and Rovelli, 2017; Dieks, 2018,

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[6] A SUQT can be always valid only in one Lorentz frame. If there existed two Lorentz frames in which a SUQT is valid, then we could arrange the temporal order of Alice's and Bob's measurements so that the predictions of the theory in the two Lorentz frames contradict each other. Similar results have also been obtained for Bell-type experiments (Leegwater, 2018; Lazarovici and Hubert, 2018).

[7] Myrvold used the Hardy state and remarked that his result obtains for any state for which a Bell inequality is derivable. Here I used the singlet state and the simpler EPR-Bohm experiment.

2019). In particular, perspectivalism assumes that measurement results are frame-dependent or hyperplane-dependent (Dieks, 2018, 2019). Besides, these theories also assume certain notion of locality, such as no superluminal causal influence, which says that causes and effects of events are no further away than permitted by the velocity of light (Martin-Dussaud et al, 2019). This prohibits the possibility that a measurement performed in a region could affect the outcomes of a measurement happening in a distant, spacelike separated region. Since the effect of "perception" at a distance manifests this possibility of superluminal causal influence, these theories (with the above notion of locality) are incompatible with special relativity.

Finally, it is worth noting that it is not so obvious whether a single-world quantum theory belongs to SUQTs. For example, in retrocausal theories and superdeterministic theories, it is unclear whether a measurement can be reversed, and whether there are even wave functions in the formulations of these theories. Moreover, even though there are wave functions in some non-ψ-ontic quantum theories, such as consistent histories (Griffiths, 2011), ψ-epistemic models (Spekkens, 2007), pragmatist approaches to quantum mechanics (Healey, 2017), and QBism (Fuchs et al, 2014), it is unclear whether the collapse of the wave function (at the epistemic level) in these theories prohibits reversible measurements. I will investigate these issues in future work.

4 Conclusions

It has been debated whether quantum theory and special relativity are compatible and whether there is a preferred Lorentz frame if they are incompatible. Bell's theorem does not give us a definite answer due to the existence of supplementary assumptions. It seems that a single-world quantum theory may be compatible with special relativity by droping one of these assumptions. Examples include relational quantum theories, retrocausal theories and superdeterminism.

In this paper, I reexamine the issue of whether a single-world unitary quantum theory is compatible with special relativity. I propose a new Gedankenexperiment, a variant of the EPR-Bohm experiment with a superobserver who can reverse a measurement. According to a single-world unitary quantum theory, in this experiment one experimenter's statistic, which is in principle inaccessible, depends on the other experimenter's choice of measurement when they are spacelike separated. The existence of this effect of "perception" at a distance at the observational level implies that a single-world unitary quantum theory is incompatible with special relativity and requires the existence of a preferred Lorentz frame. Since this new analysis does not rely on the supplementary measurement independence assumption in the proof of Bell's theorem, it provides a more general proof of the incompatibility between a single-world unitary quantum theory and special relativity. However, more work needs to be done to determine whether this incompatibility result is valid in some single-world quantum theories which can avoid the nonlocality result of Bell's theorem.

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