Understanding Branching in the Many-worlds Interpretation of Quantum Mechanics

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Abstract

It has been recently debated whether world branching in the many-worlds interpretation of quantum mechanics (MWI) is global or local. In this paper, I present a new analysis of the branching process in MWI. First, I argue that branching is not global. Next, I argue that branching is not necessarily local either, and it can be nonlocal for particles being in an entangled state. Third, I argue that for nonlocal branching there is action at a distance in each branching world, and as a result, there is also a preferred Lorentz frame in the world. However, the action at a distance in each world is apparent in the sense that there is no action at a distance and resulting preferred Lorentz frame in the whole worlds, and thus MWI is consistent with special relativity.

1 Introduction

Branching is the most important process in the many-worlds interpretation of quantum mechanics (MWI). According to the modern formulation of MWI, world branching results from environmental-induced decoherence, which is an effectively irreversible process that can form temporally extended and stable quasi-classical worlds (Wallace, 2012). It has been a controversial issue whether branching is global or local and whether there is action at a distance in the theory (see, e.g. Sebens and Carroll, 2018; McQueen and Vaidman, 2019; Ney, 2024). In this paper, I will present a new analysis of the branching process in MWI.

The rest of this paper is organized as follows. In Section 2, I first argue that branching is not global. Global branching is consistent neither with the decoherence-based formulation of MWI nor with quantum mechanics and experiments. In Section 3, I then argue that branching is not necessarily local either, and it can be nonlocal for particles being in an entangled state. In Section 4, I further argue that there is (apparent) action at a distance in each nonlocally branching world, and what is nonlocally changed is a particle's extrinsic properties relative to the world. In Section 5, I analyze whether action at a distance also exists in the whole worlds. Although there is a potential objection to the standard negative answer to this question, I argue that there is no action at a distance and resulting preferred Lorentz frame in the whole worlds, and thus MWI is consistent with special relativity. Conclusions are given in the last section.

2 Why branching is not global

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:

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

According to the linear Schrödinger equation, the state of the composite system after Alice's z-spin measurement will be an entangled superposition of Alice recording z-spin up and Alice recording z-spin down:

$$\begin{aligned} & \frac{1}{\sqrt{2}}(\left|\uparrow_z\right\rangle_a \left|\downarrow_z\right\rangle_b - \left|\downarrow_z\right\rangle_a \left|\uparrow_z\right\rangle_b) \left|ready\right\rangle_A \left|ready\right\rangle_B \\ \rightarrow \quad & \frac{1}{\sqrt{2}}(\left|\uparrow_z\right\rangle_a \left|\downarrow_z\right\rangle_b \left|\uparrow_z\right\rangle_A - \left|\downarrow_z\right\rangle_a \left|\uparrow_z\right\rangle_b \left|\downarrow_z\right\rangle_A) \left|ready\right\rangle_B \end{aligned} \tag{2}$$

Due to environmental-induced decoherence in Alice's lab (I omit the environment state in the above formula), Alice's reduced density matrix will be (almost) diagonalized:

$$\rho_A \approx \frac{1}{2}(\left|\uparrow_z\right\rangle_A \left\langle\uparrow_z\right|_A + \left|\downarrow_z\right\rangle_A \left\langle\downarrow_z\right|_A) \tag{3}$$

According to the modern formulation of MWI, decoherence causes branching, and thus Alice branches into two copies, which may be called Alice+ and Alice-, after her measurement, each of which obtains a definite result, either z-spin up or z-spin down. Correspondingly, there are two worlds, Alice+'s world and Alice-'s world, in each of which the measured particle a also has a definite spin state, either $\left|\uparrow_z\right\rangle_a$ or $\left|\downarrow_z\right\rangle_a$.

Now an interesting question arises: does Bob also branch after Alice's measurement? According to some authors (Sebens and Carroll, 2018; Ney, 2024), since the post-measurement state can also be written as:

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\begin{aligned}
& \frac{1}{\sqrt{2}}(\left|\uparrow_z\right\rangle_a \left|\downarrow_z\right\rangle_b \left|\uparrow_z\right\rangle_A - \left|\downarrow_z\right\rangle_a \left|\uparrow_z\right\rangle_b \left|\downarrow_z\right\rangle_A) \left|ready\right\rangle_B \\
= \; & \frac{1}{\sqrt{2}}(\left|\uparrow_z\right\rangle_a \left|\downarrow_z\right\rangle_b \left|\uparrow_z\right\rangle_A \left|ready\right\rangle_B - \left|\downarrow_z\right\rangle_a \left|\uparrow_z\right\rangle_b \left|\downarrow_z\right\rangle_A \left|ready\right\rangle_B)
\end{aligned}
$$

Bob will also branch into two copies, Bob+ and Bob-, after Alice's measurement, although they are the same as the original Bob. In particular, Bob+ is in Alice-'s world (in which Alice- obtains the result of z-spin down), and if he measures the z-spin of particle b, he will obtain the result of z-spin up with certainty, while Bob- is in Alice+'s world (in which Alice+ obtains the result of z-spin up), and if he measures the z-spin of particle b, he will obtain the result of z-spin down with certainty. Such branching has been called global branching. On this view, "branching happens throughout the whole wave function whenever it happens anywhere. When the universal wave function splits into multiple distinct and effectively non-interacting parts, the entire world splits - along with every object and agent in it." (Sebens and Carroll, 2018).

In the following, I will argue that this view of global branching cannot be right. First of all, if one accepts the modern formulation of MWI, according to which branching results from decoherence, then clearly Bob does not branch immediately after Alice's measurement, since Bob's state remains the same and it does not decohere after Alice's measurement. On this standard view, only after Bob's reduced density matrix becomes a mixed state and also (almost) diagonalized with respect to definite result states, can we say that Bob branches into multiple copies.

Second, even if one denies this standard view and insists that branching is not (only) caused by decoherence, global branching is inconsistent with quantum mechanics and experiments either. According to the view of global branching, after Alice's measurement, Bob will branch into two identical copies, Bob+ (in Alice-'s world) and Bob- (in Alice+'s world), and if each of them measures the spin of particle b, he will obtain a definite result, either z-spin up or z-spin down, with certainty. However, quantum mechanics and experiments tell us that after Alice's measurement, if Bob (or the identical Bob+ or Bob-) measures the spin of particle b, he will obtain z-spin up or z-spin down with probability 1/2. Moreover, quantum mechanics and experiments in principle permit that Bob can measure the whole entangled superposition of Alice and particles a and b, such as the interference between its two branches. By contrast, if Bob branches and each of his copies is in one of Alice's copies' worlds, then each of Bob's copies cannot measure the whole entangled superposition of Alice.[1]

Finally, as noted by Sebens and Carroll (2018), “The non-local nature of the globally-branching view might cause some discomfort. It implies that observers here on Earth could be (and almost surely are) branching all the time, without noticing it, due to quantum evolution of systems in the Andromeda Galaxy and elsewhere throughout the universe.” In fact, the real issue lines not in the strange features such as nonlocality of global branching, but in that there is no sensible justification for the existence of such global branching. Immediately after Alice’s measurement, the influence of the measurement has not arrived at Bob’s lab, and Alice and Bob are still spacelike separated. In addition, there is neither quantum entanglement nor classical relation between Alice and Bob before the measurement (e.g. they are not a married couple, which is unlike the situation in the classical example). Thus, it is arguable that Alice’s measurement cannot result in any immediate change of Bob, either intrinsic or extrinsic (cf. Ney, 2024).

3 Must branching be local?

Based on the above analysis, it can be argued that Bob does not branch immediately after Alice’s measurement. Moreover, it is also inappropriate to say that Bob is located in both Alice+’s and Alice-’s worlds (McQueen and Vaidman, 2018; Ney, 2024). The better expression should be that Bob does not exist in Alice’s worlds and he is outside these worlds (before the influence of Alice’s measurement arrives at Bob’s lab). According to Wallace (2012, p.307), “branching is not a global phenomenon”, and since decoherence takes time, the branching event “propagates outwards at the speed of whatever dynamical interaction is causing decoherence — in practice, it propagates out at the speed of light.” Does this mean that branching must be local? As we will see, the answer is negative.

Let’s first consider particle a in Alice’s lab. According to the previous analysis, Alice branches into two copies, Alice+ and Alice-, after her measurement, each of which obtains a definite result, either z-spin up or z-spin down. Correspondingly, there are two worlds, Alice+’s world and Alice-’s world, in each of which the measured particle a has a definite spin state, either $|\uparrow_z\rangle_a$ or $|\downarrow_z\rangle_a$. Note that before Alice’s measurement, particle a is in an entangled superposed spin state. In this sense, we may say that particle a also branches into $a+$ and $a-$ after Alice’s measurement.[2] This branching process for particle a is local.

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[1] If someone can measure the whole entangled superposition of Alice or both Alice+’s and Alice-’s worlds, then it will make no sense to say that she is in one of these worlds; rather, it is better to (or we should) say that she is outside these worlds.

[2] As Ney (2024) has pointed out, it is incoherent to suppose that a macroscopic object branches, but the particles that compose it do not.

How about particle b in Bob's lab then? It is arguable that particle b, like particle a, should also branch into two copies, $b+$ and $b-$, after Alice's measurement. Concretely speaking, before Alice's measurement, particle b is in an entangled superposed spin state, while after Alice's measurement, in Alice+'s world (where particle $a+$ has a definite spin state $|{\uparrow_z}\rangle_a$) one copy of particle b, $b-$, has a definite spin state $|{\downarrow_z}\rangle_b$, and in Alice-'s world (where particle $a-$ has a definite spin state $|{\downarrow_z}\rangle_a$) the other copy of particle b, particle $b+$, has a definite spin state $|{\uparrow_z}\rangle_b$. If this is not the case, then when Alice+ or Alice- arrives at Bob's lab and measures the z-spin of particle b, her result will be not 100% anti-correlated with her previous result of measuring particle a and thus not consistent with the Born rule. Note that Alice's travel does not change the state of particle b. Moreover, if particle b does not branch (after Alice's measurement and) before Alice measures its z-spin, then its state will be the same for Alice+ and Alice-, and thus the probability distribution for Alice+'s and Alice-'s measurement results will be the same. But this also contradicts the Born rule, according to which Alice+'s result is z-spin down with certainty, and Alice-'s result is z-spin up with certainty.

It can be seen that the branching of particle b due to Alice's measurement is obviously nonlocal. The particle b in Bob's lab branches into two copies, $b+$ and $b-$, immediately after Alice's measurement in her lab, no matter how far away these two labs are separated in space. Due to particle b's branching and the anti-correlation between the states of $b+$ and $b-$ and the states of Alice- and Alice+ in both worlds, when Bob measures particle b and branches later, his result will be always anti-correlated with Alice's result in each world; in Alice-'s world, in which Alice obtains the result of z-spin down, there is Bob+ and he obtains the result of z-spin up, and in Alice+'s world, in which Alice obtains the result of z-spin up, there is Bob- and he obtains the result of z-spin down. Moreover, the anti-correlation between Alice's result and Bob's result is also nonlocal due to the nonlocal branching of particle b. In other words, the nonlocality of the anti-correlation between Alice's result and Bob's result can be and should be expained by the nonlocal branching of particle b.

4 Understanding nonlocal branching

Then, how to understand the nonlocal branching of particle b? It can be expected that a true understanding of such nonlocal branching will be the key to understanding the nature of nonlocality in MWI.

First of all, Wallace's (2012) analysis of local branching cannot help us. Wallace's analysis is valid for Alice and particle a in her lab, as well as for Bob who is in a product state with Alice. However, his analysis does not apply to particle b in Bob's lab, which is entangled with particle a in

Alice's lab. In fact, Wallace did not consider the situation of particle b and the question of whether particle b branches after Alice's measurement. As argued above, although branching is not a global phenomenon, it may be nonlocal for entangled particles such as particle b.

Next, it can be argued that there is action at a distance in each branching world for nonlocal branching. In the above experiment, Alice's measurement first causes her particle a's branching, then due to the entanglement between the particles a and b, Bob's particle b also branches at the same time as Alice's particle a. Since Alice's and Bob's labs are spacelike separated, Alice's measurement causes the branching of Bob's particle b nonlocally. Recall that before Alice's measurement the branching particle $b+$ or $b-$ (or the original b) was in an entangled superposition of z-spin up and z-spin down, while after Alice's measurement it is in a definite state of z-spin up (in Alice-'s world) or z-spin down (in Alice+'s world). If each world continuously exists in time as usually assumed, e.g. before Alice's measurement Alice+'s world also exists and it is the same as Alice's world, then in each of Alice+'s and Alice-'s worlds, her measurement results in the instantaneous state change of particle b. In other words, in each of these nonlocally branching worlds there is action at a distance.[3]

Moreover, there will be also a preferred Lorentz frame in which the action at a distance is intantaneous in each of these nonlocally branching worlds. For example, particle b branches into $b+$ and $b-$ immediately after Alice's measurement in this preferred Lorentz frame. In other Lorentz frames, Alice's measurement may precede or follow particle b's branching. In special relativity, 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. Thus nonlocal branching violates the Lorentz invariance of the temporal relation between cause and effect in each nonlocally branching world. Certainly, due to the no-signaling theorem, such nonlocal branching does not lead to superluminal signaling in these worlds.

Third, the reality of the action at a distance in each nonlocally branching world depends on the reality of these worlds. Although what is nonlocally changed is arguably particle b's extrinsic properties relative to Alice or Alice's worlds, if these worlds are real as usually thought, then these extrinsic properties relative to these worlds should be also taken as b's intrinsic properties *in* these worlds,[4] and thus their changes should be considered as real

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[3] The state change of particle b in each world can be called the effective collapse of the wave function of particle b. This is in contrast with the real (dynamical) collapse of the wave function in collapse theories. The action at a distance in each world can also be called effective action at a distance.

[4] These intrinsic properties of particle b in each world are incomplete. As will argued later, the complete intrinsic properties of particle b in the whole worlds is not changed by Alice's measurement, and thus there is no real action at a distance and resulting violation

as these worlds. In this sense, there is real action at a distance in each nonlocally branching world, whose existence is inconsistent with special relativity.[5]

Finally, it is worth noting that the above state change of particle b in each world is essentially different from the change of relation in the classical case. In the classical case, when a man dies her wife immediately becomes a widow, but this change of relation or appellation does not correspond to any real state change. And thus there is no real action at a distance and resulting violation of special relativity in this classical case. By contrast, in the above quantum case, the state change of particle b in each world is real. For example, in Alice+'s world, particle $b-$'s state changes from an entangled superposition of z-spin up and z-spin down to a definite state of z-spin down due to her measurement. Thus there is real action at a distance and resulting violation of special relativity in each world in the quantum case.

5 Is MWI consistent with relativity?

As is well known, in single-world quantum theories such as collapse theories, there is real action at a distance and thus these theories are not consistent with special relativity. According to the above analysis, in MWI there is also similar action at a distance in each nonlocally branching world. Now the question is: is there real action at a distance in the whole worlds? The standard answer, according to many authors, is definitely negative.

The usual reason of why MWI does not involve action at a distance is as follows. For the nonlocal branching of particle b in the above example, Alice's measurement does not change b's quantum state or its reduced density matrix, which has been $\rho_b = \frac{1}{2}(|{\uparrow_z}\rangle_b \langle{\uparrow_z}\, |_b + |{\downarrow_z}\rangle_b \langle{\downarrow_z}\, |_b)$ before and after Alice's measurement. This is ensured by the local Schrödinger dynamics in MWI. Since the quantum state is a complete representation of the ontic state in MWI, we may say that particle b's ontic state or intrinsic properties are not changed by Alice's measurement, and thus there is no real action at a distance in the whole worlds for particle b's nonlocal branching. On this view, the action at a distance in each nonlocally branching world is apparent, whose existence is due to the incomplete representation of quantum states in each of these worlds. Thus, nonlocal branching is still consistent with special relativity in the whole worlds.

There is a potential objection to the above analysis. The crux lies in that b's reduced density matrix is in fact not a complete representation

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of special relativity in the whole worlds in MWI.

[5] This result can be more readily understood when considering the case of nonlinear quantum mechanics where the no-signaling theorem is violated. In that case, the action at a distance in each nonlocally branching world can be used to realize superluminal signaling in these worlds, and thus it is certainly real.

of its ontic state, but a mere representation of the maximum information that experiments can obtain. That Alice's measurement does not change b's reduced density matrix ensures that experiments cannot detect any change of particle b due to Alice's measurement and thus there is no superluminal signaling. But it does not ensure that b's ontic state must not change, and it is also possible that b's ontic state changes but the change cannot be detected by any experiments.

Since particle b is entangled with particle a, its ontic state should not only include the property represented by its reduced density matrix, but also include the entangled property co-possessed with particle a. It can be seen that the entangled property of particles a and b are indeed changed by Alice's measurement even in the whole worlds (e.g. as seen by Bob); before Alice's measurement, the spin of particles a and b are 100% anti-correlated in any direction, while after her measurement, the spin of particles a and b are 100% anti-correlated only in the measured z direction (see (2)).

However, that the entangled property of particles a and b is changed does not mean that particle b's part of the entangled property or particle b's entangled property must change. It can be the case that only particle a's entangled property changes, but particle b's entangled property does not change. In this case, the entangled property of particles a and b can also be changed. For example, before Alice's measurement, the spin of particles a and b are 100% anti-correlated in every direction. After Alice's measurement, the spin of particles b does not change in each direction, and the spin of particles a does not change only in the measured z direction. Then, the spin of particles a and b can still keep 100% anti-correlated in the measured z direction, but not in other directions. Certainly, the more direction reason that particle b's entangled property is not changed by Alice's measurement is that the measuring interaction happens between Alice and particle a, not between Alice and particle b (and the entanglement between particles a and b does not mediate or transmit interaction either).

Finally, I must admit that the above analysis of particle b's nonlocal branching is still not satisfying at least in one key aspect. That is, it does not use a clear ontology for quantum states in space and time to explain the nonlocal branching. In my view, only after we find the true ontology for quantum states (especially for entangled states) can we fully understand nonlocal branching, since the nonlocal branching results from the nonlocal entangled states. Admittedly, it is still a debated and unsolved issue what ontology the quantum state really represents. It is widely thought by the proponents of MWI that the ontology represented by the quantum state exists in our three-dimensional space. But how an entangled state, which is defined in a 3N-dimensional space, ontologically exists in three-dimensional space is still unknown. For example, spactime state realism does not provide an ontology in three-dimensional space for the entangled properties of particles being in an entangled state (Wallace and Timpson, 2010), and thus it cannot help us understand nonlocal branching. By contrast, my suggested interpretation of the wave function in terms of random discontinuous motion of particles provides a possible complete ontological picture for entangled states in our three-dimensional space and thus it might help explain nonlocal branching (Gao, 2017, 2020, 2021, 2022, 2023). I will study this possibility in future work.

6 Conclusions

It is still a controversial issue whether branching is global or local and whether there is action at a distance in MWI. In this paper, I present a new analysis of the branching process in the theory. Although branching is arguably not global, it is not necessarily local either, and it can be nonlocal for particles being in an entangled state. My analysis suggests that there is action at a distance in each nonlocally branching world. However, the action at a distance in each world is apparent in the sense that there is no action at a distance in the whole worlds, and thus MWI is consistent with special relativity. It is my view that only after we find the true ontology for quantum states, especially for entangled states, can we fully understand nonlocal branching and the resulting nonlocality in MWI.

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