Does the Universe Split Everywhere at Once? Rethinking Branching and Nonlocality in the Many-Worlds Interpretation of Quantum Mechanics

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Abstract

The nature of branching in the many-worlds interpretation (MWI) of quantum mechanics remains an open question, particularly regarding its locality and compatibility with special relativity. This paper challenges the conventional view that branching is either global or local, demonstrating instead that it is nonlocal for entangled systems. Through a new analysis of the EPR-Bohm experiment, I argue that global branching has several potential issues and can hardly be justified. At the same time, I argue that branching cannot be entirely local, as entangled particles exhibit simultaneous, spacelike-separated branching, manifesting an apparent action at a distance within individual worlds. However, while nonlocal branching suggests the emergence of a preferred Lorentz frame within each world, the multiverse as a whole retains full Lorentz invariance, ensuring no superluminal signaling. By refining the ontology of branching and resolving tensions between MWI and relativistic constraints, this analysis may help advance our understanding of quantum nonlocality and also strengthen MWI's standing as a viable interpretation of quantum mechanics.

1 Introduction

The many-worlds interpretation (MWI) of quantum mechanics, first proposed by Hugh Everett III in 1957, offers a radical solution to the measurement problem by positing that all possible outcomes of a quantum measurement occur in different worlds (Everett, 1957; Vaidman, 2021). While this interpretation avoids the need for wavefunction collapse, it introduces the contentious concept of *branching* — a process where the universe splits into multiple worlds whenever a quantum event occurs. Over the past decades, the modern formulation of MWI has refined this idea, grounding branching in environmental-induced decoherence, a process that explains the emergence of stable, quasi-classical worlds (Wallace, 2012). However, critical questions remain unresolved: Is branching *global*, happening throughout the entire universe instantaneously (Sebens and Carroll, 2018; Ney, 2024), or is it *local*, propagating at finite speeds? (Wallace, 2012; McQueen and Vaidman, 2019) How does nonlocality in entangled systems influence branching? Most importantly, can MWI reconcile its branching mechanism with the principles of special relativity?

This paper addresses these questions through a novel analysis of branching in MWI. Section 2 critiques the global branching view, arguing that it has several potential issues and can hardly be justified. Section 3 challenges the assumption that branching must be strictly local, demonstrating that entangled particles exhibit *nonlocal branching*. Section 4 explores the implications of nonlocal branching, revealing apparent action at a distance within individual worlds. Section 5 argues that while each branching world may violate Lorentz invariance, the entire multiverse remains consistent with special relativity. Finally, Section 6 concludes by emphasizing the need for a clearer ontology of quantum states to fully understand nonlocality in MWI.

2 Is branching global? A critical examination

2.1 The EPR-Bohm experiment and global branching

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 in the result states:

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

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:

$$\begin{aligned} & \frac{1}{\sqrt{2}}(\left|\uparrow_z\right\rangle_a \left|\downarrow_z\right\rangle_b \left|\uparrow_z\right\rangle_A - \left|\downarrow_z\right\rangle_a \left|\uparrow_z\right\rangle_b \left|\downarrow_z\right\rangle_A) \left|ready\right\rangle_B \\ = & \frac{1}{\sqrt{2}}(\left|\uparrow_z\right\rangle_a \left|\downarrow_z\right\rangle_b \left|\uparrow_z\right\rangle_A \left|ready\right\rangle_B - \left|\downarrow_z\right\rangle_a \left|\uparrow_z\right\rangle_b \left|\downarrow_z\right\rangle_A \left|ready\right\rangle_B). \end{aligned} \tag{4}$$

Bob will also branch into two copies, Bob+ and Bob-, after Alice's measurement. 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).

2.2 Problems with global branching

In the following, I will argue that the global branching view is problematic.

2.2.1 Decoherence and the timing of branching

The modern modern formulation of MWI ties branching to decoherence — a process where a system interacts with its environment, erasing quantum coherence. Crucially, decoherence is local and gradual; it propagates at finite speeds (typically subluminal) as interactions spread through the environment. If one accepts the modern MWI, according to which branching results from decoherence, then clearly Bob does not branch immediately after Alice's measurement, since Bob's state 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. Thus it is obvious that the view of global branching is inconsistent with the standard view that no decoherence no branching.

However, this does not imply that global branching is impossible; rather, it means that if global branching happens, then it cannot result from decoherence, and one must find another cause for it. For example, Ney (2024) argued that Alice's measurement causes Bob's global branching, but the change in Bob is a "Cambridge change", and it does not require any physical influence to travel to Bob. This seems to be the only way to make sense of global branching. Since there is no quantum entanglement between Alice and Bob before the measurement, and 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, it is arguable that Alice's measurement cannot result in any real, intrinsic change of Bob. In the following, I will argue that no matter what causes global branching, the view itself has several potential issues.

2.2.2 The problem of amplitude loss

According to the view of global branching, after Alice's measurement, Bob will branch into two 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. By contrast, quantum mechanics predicts that after Alice's measurement, if Bob measures the spin of particle b, he will obtain z-spin up or z-spin down with probability 1/2. This is the Born rule. Then, MWI with global branching needs to explain why experiments seem to indicate that Bob's spin-up or spin-down result has a probability of 1/2 or why experimental results seem to satisfy the Born rule as predicted by quantum mechanics. However, it is arguable that the view of global branching has no resources to solve this probability problem of MWI quantitatively, since once Bob branches, in each world of Bob+ and Bob-, the quantum state no longer has an amplitude $1/\sqrt{2}$ or α that determines the probability 1/2 or $|\alpha|^2$ (see (4)).

As a result, global branching exacerbates MWI's probability problem. If Bob branches immediately after Alice's measurement, his post-measurement state in each world lacks the amplitude coefficients needed to recover the Born rule. Without these coefficients, there is no basis for assigning probabilities to outcomes, undermining MWI's ability to explain why observers perceive statistical regularities. It remains to be seen whether global branching can resolve this issue of amplitude loss.

2.2.3 Global branching is not Cambridge changes

Ney (2024) suggests that Bob's global branching is a mere Cambridge change - a relational alteration without intrinsic physical consequences. However, as I will argue below, this conflicts with the reality of quantum states in MWI.

According to the view of global branching, after Alice's measurement (and before Bob measures particle b), relative to each of Bob+ and Bob-, the state of particle b will change from a mixed state $\frac{1}{2}(|\uparrow_z\rangle_b \langle\uparrow_z|_b + |\downarrow_z\rangle_b \langle\downarrow_z|_b)$ to a pure state or a definite spin state, either $|\uparrow_z\rangle_b$ or $|\downarrow_z\rangle_b$. This means that the state of particle b relative to Bob is changed by Alice's measurement, just like the state of particle a relative to Alice is changed by Alice's measurement. Since quantum states are real in MWI, the state change of b relative to Bob is not a mere Cambridge change but a real physical change. Moreover, the state of particle b relative to Bob cannot change without an interaction happening between them (e.g. Bob measuring particle b), while Alice's measurement does not result in their interaction. Thus, it is arguable that Bob does not branch after Alice's measurement.

2.2.4 The problem of superposition measurement

Quantum mechanics and experiments permit that after Alice's measurement, Bob can in principle measure the whole entangled superposition of Alice and particles a and b (if they are all in the same lab), such as the interference between its two branches. However, if Bob branches and each of his copies is in one of Alice's copies' worlds, then it is arguable that each of Bob's copies cannot measure the whole entangled superposition of Alice. If someone can measure the whole entangled superposition of Alice or both Alice+'s and Alice-'s worlds, then it seems to 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.

To sum up, the view of global branching has several potential issues. In order to justify this view, one needs to answer why and how the state of particle b relative to Bob is changed by Alice's measurement, without an interaction happening between them, e.g. Bob's measurement of particle b. As noted by Sebens and Carroll (2018), "The non-local nature of the globally-branching view might cause some discomfort." In my opinion, the real issue lies not in the strange features of global branching such as its nonlocality, but in that its existence can hardly be justified.

3 Must branching be local? The case for nonlocal branching

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 is 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 for entangled states.

3.1 Existence of particle branching

Let's first consider particle a in Alice's lab. Before Alice's measurement, particle a is in an entangled superposed spin state. After Alice's measurement, Alice branches into two copies, Alice+ and Alice-, 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 $|\downarrow_z\rangle_a$. In this sense, we may say that particle a also branches into two copies, $a+$ (being in the definite spin state $|\uparrow_z\rangle_a$ in Alice+'s world) and $a-$ (being in the definite spin state $|\downarrow_z\rangle_a$ in Alice-'s world), after Alice's measurement. This ensures that when Alice+ or Alice- measures the z-spin of particle a again, she will obtain the same result as before with certainty. It can be seen that the branching of particle a due to Alice's measurement is local.

Here it seems necessary to clarify the meaning of the branching of a particle. It is usually thought that in the modern formulation of MWI, branching, which is required to make sense of the emergent, macroscopic world, appears only when we enter into a kind of macroscopic level of description, e.g. for a measuring device or an observer. However, as Ney (2024) has argued, it is incoherent to suppose that a macroscopic object branches, but the particles that compose it do not. In addition, when a particle is entangled with a macroscopic object such as a measuring device or an observer after a measurement, one may argue that the particle will also branch relative to the measurer as the measurer branches. Otherwise when each copy of the measurer measures the particle again, she will not obtain the same result as before with certainty, which contradicts the Born rule. As we will see later, an analysis of the branching of entangled particles will be important for understanding nonlocal quantum correlation in MWI.

3.2 Entanglement and nonlocal branching

Now that particle a branches after Alice's measurement, how about particle b in Bob's lab which is entangled with particle a? It is arguable that after Alice's measurement, particle b, like particle a, should also branch into two copies, $b+$ and $b-$, which exist in the worlds of Alice- and Alice+, respectively. 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 relative to Alice (after Alice's measurement of particle a 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.

One might prefer another way of thinking about branching in MWI. That is, after Alice's measurement, particle b is still in a superposition, and it is just that Alice+ is in one branch of the superposition and Alice- is in the other. However, this is equivalent to say that particle b branches relative to Alice (or as seen by Alice). In both cases, in Alice+'s world, particle b or its copy $b-$ has a definite spin state $|{\downarrow_z}\rangle_b$, and in Alice-'s world, particle b or its copy $b+$ has a definite spin state $|{\uparrow_z}\rangle_b$. Either way, after Alice's measurement, the change of particle b (from a mixed state to a pure state) relative to Alice, like the change of particle a relative to Alice, is not a Cambridge change, since the wave function is real in MWI (cf. Ney, 2024).

Here one may also see more clearly why Bob, unlike particle b, does not branch after Alice's measurement. The reason is that Bob is not entangled with Alice (and neither he interacts directly with Alice), and thus Alice's measurement does not affect Bob, such as causing him branch. By contrast, particle b (as well as particle a) is entangled with Alice after her measurment, and the Born rule requires that it must branch relative to Alice in a way consistent with Alice's branching.

It can be seen that the branching of particle b (relative to Alice) due to Alice's measurement of particle a is nonlocal. Immediately after Alice's measurement in her lab, the particle b in Bob's lab branches into two copies, $b+$ and $b-$, at the same time as Alice branches, no matter how far away these two labs are separated in space. Due to 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 explained 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.

4.1 Limitation of local branching

Here 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 and spacelike separated from 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.

4.2 Action at a distance in individual worlds

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 thought, 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.[1]

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 particle b's intrinsic properties *in* these worlds,[2] and thus their changes should be considered as real 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.[3]

4.3 Existence of a preferred Lorentz frame

Nonlocal branching also necessitates a preferred Lorentz frame where branching events are synchronized. In other words, 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, in this preferred Lorentz frame, particle b branches into $b+$ and $b-$ immediately after Alice's measurement. While in other Lorentz frames, particle b's branching may precede or follow Alice's measurement. This means that branching events are frame-dependent, and observers in different frames may perceive branching orders differently.

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 (e.g. Alice's measurement) and effect (e.g. particle b's branching) in each nonlocally branching world. Certainly, due to the no-signaling theorem, such nonlocal branching does not lead to superluminal signaling in each world.

Here it is worth emphasizing again that the above state change of particle b in each world is essentially different from a Cambridge change or the change of relation in the classical case. In the classical case, when a man

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[1] The state change of particles a and b in each world can be regarded as one kind of effective collapse of their wave function. This is in contrast with the real (dynamical) collapse of the wave function in collapse theories. Then, the action at a distance in each world is also effective, relative only to the world. As Vaidman (1994) said, "in the created worlds we obtain, effectively, nonlocal changes."

[2] These intrinsic properties of particle b in each world are incomplete. As I will argue 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 of special relativity in the whole worlds in MWI.

[3] 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, if assuming MWI is still valid, then 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.

dies her wife immediately becomes a widow, and 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 preferred Lorentz frame 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 preferred Lorentz frame in each (nonlocally branching) world in the quantum case.

5 MWI and special relativity: A reconciliation

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.

5.1 The standard argument

The usual reason 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 appearance 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.

In short, nonlocal branching implies that particle b's state changes instantaneously in each world, resembling action at a distance. However, this action is world-relative: In the global multiverse, b's reduced density matrix remains unchanged, preserving the no-signaling theorem. Thus, nonlocal branching is an emergent phenomenon within individual worlds, not a fundamental feature of the multiverse.

5.2 Objection and reply

There is a potential objection to the above argument. The key is to realize that b's reduced density matrix is not a complete representation of its ontic state, but a 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 imply 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 every 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 particle b does not change in each direction, while the spin of particle a changes in each direction except 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.[4] Certainly, the more direct 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).

5.3 Entanglement is the key

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

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[4] Note that this example assumes a hidden-variables view. In my opinion, the probability problem of MWI can only be solved in an agent-independent way by introducing certain hidden variables (see Gao, 2021, 2022, 2023).

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 ontic state 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 high-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, the interpretation of the wave function in terms of random discontinuous motion of particles provides a possible 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 another paper.

6 Conclusions

The nature of branching in the many-worlds interpretation (MWI) of quantum mechanics has long been obscured by debates over its locality and compatibility with relativity. This paper aims to resolve key tensions by demonstrating that branching is neither strictly global nor purely local, but *nonlocal* for entangled systems. By rigorously analyzing the EPR-Bohm scenario, I have argued that global branching — which posits instantaneous, universal splitting of all systems — fails to align with decoherence-driven accounts of MWI, introduces inconsistencies with the Born rule, and leads to paradoxical implications for superposition measurements. Conversely, while local branching captures the causal propagation of decoherence, it inadequately addresses the nonlocal correlations inherent in entangled states. Compared with these two views, nonlocal branching, according to which entangled particles branch simultaneously across spacelike-separated regions, manifesting apparent action at a distance within individual worlds, provides a more coherent explanation of quantum correlations. Crucially, this nonlocality is apparent rather than fundamental. The multiverse as a whole retains a Lorentz-invariant structure, with no preferred Lorentz frame or superluminal influence across all worlds. This reconciles MWI with special relativity while preserving its capacity to explain quantum nonlocality.

By clarifying the interplay between branching, entanglement, and relativity, this analysis strengthens MWI's standing as a robust framework for relativistic quantum theory. It also highlights unresolved ontological challenges: a full account of nonlocal branching demands a deeper understanding of how entangled states exist in space and time. This gap will be addressed in future work.

References

[1] Everett, H. (1957). Relative State Formulation of Quantum Mechanics, Review of Modern Physics 29, 454-462.

[2] Gao, S. (2017). The Meaning of the Wave Function: In Search of the Ontology of Quantum Mechanics. Cambridge: Cambridge University Press.

[3] Gao, S. (2020). A Puzzle for the Field Ontologists. Foundations of Physics 50, 1541-1553.

[4] Gao, S. (2021). Time Division Multiverse: A New Picture of Quantum Reality. http://philsci-archive.pitt.edu/20055/.

[5] Gao, S. (2022). On Bell's Everett (?) Theory. Foundations of Physics 52, 89.

[6] Gao, S. (2023). Many Worlds with both "And" and "Or". https://philsci-archive.pitt.edu/21855/

[7] McQueen, K and L. Vaidman. (2019). In defence of the self-location uncertainty account of probability in the many-worlds interpretation. Studies in History and Philosophy of Modern Physics, 66, 14-23.

[8] Ney, A. (2024). The Argument from Locality for Many Worlds Quantum Mechanics. Journal of Philosophy (forthcoming).

[9] Sebens, C. and S. Carroll. (2018). Self-locating Uncertainty and the Origin of Probability in Everettian Quantum Mechanics. The British Journal for the Philosophy of Science, 69, 25-74.

[10] Vaidman, L. (1994). On the Paradoxical Aspects of New Quantum Experiments. PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association, 1994, 211-217.

[11] Vaidman, L. (2021). Many-Worlds Interpretation of Quantum Mechanics. The Stanford Encyclopedia of Philosophy (Fall 2021 Edition), Edward N. Zalta (ed.). https://plato.stanford.edu/archives/fall2021/entries/qm-manyworlds/.

[12] Wallace, D. (2012). The Emergent Multiverse: Quantum Theory according to the Everett Interpretation. Oxford: Oxford University Press.

[13] Wallace, D. and C. G. Timpson (2010). Quantum Mechanics on Spacetime I: Spacetime State Realism. The British Journal for the Philosophy of Science 61, pp. 697-727.