The Many-Worlds Interpretation of Quantum Mechanics is the Only Way to Avoid Action at a Distance

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Abstract

It is argued that, keeping the standard paradigm of a scientific theory, the only way to avoid (spooky) action at a distance of quantum mechanics is to accept the existence of parallel worlds created at every quantum measurement. Einsten's boxes and Greenberger-Horne-Zeilinger scenario are analyzed in the framework of the many-worlds interpretation, Bohmian mechanics, and Ghirardi-Rimini-Weber collapse theory.

1 Introduction

A century after its creation, quantum theory does not have a consensus on its interpretation. Quantum effects break the intuition of classical physics and do not have explanations in terms of everyday experience. In my view, Vaidman (2002), the main reason for accepting a philosophically radical many-worlds interpretation of quantum mechanics (MWI) that includes a multitude of parallel worlds similar to the one we experience is that it avoids action at a distance.

A simple scenario that apparently demonstrates my claim that only the MWI can avoid action at a distance is Einstein's boxes, Norsen (2005). The particle is placed in two spatially separate boxes. A gedanken experiment achieving this is presented in Fig. 1. A particle is placed in the left part of a double box with a semitransparent wall between the left and right sides. The transparency is set such that during the period T the particle tunnels from one side to the other and returns to the original state, but we wait only time $\frac{T}{4}$. According to the quantum description, the wavefunction of the particle is spread in the boxes, so in some sense, every box has a half particle inside it. Opening and looking in box A invariably changes the description of the other. After the measurement in A, the other box, B, has either one particle or nothing. Both options are different from the description of box B before the measurement. The action in A changes reality in B, which might be at an arbitrarily large distance from A.

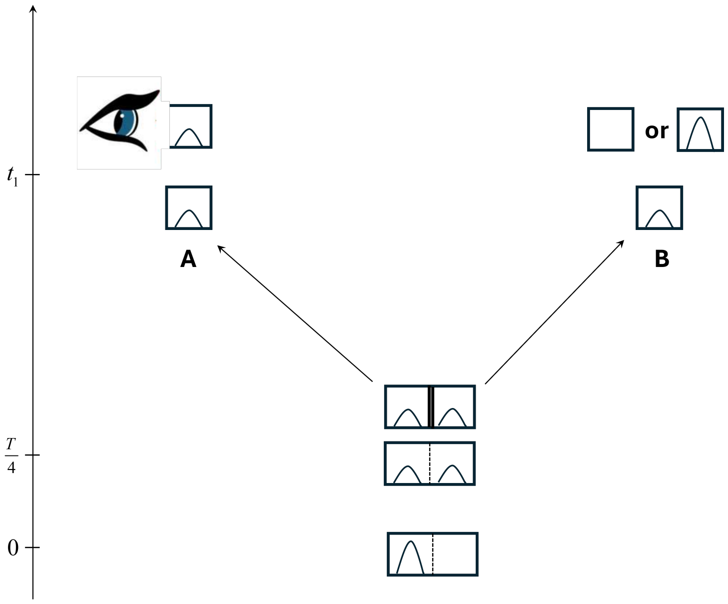

Figure 1: **Einstein's boxes.** At the beginning the particle is placed in the left side of a box with two parts and semitransparent wall between them. At time $\frac{T}{4}$ half of the quantum wave penetrates to the right part of the double box. At this moment the semitransparent wall is replaced by two fully reflecting walls, the box split into two boxes which are moved to separate locations A and B. Now, in box B there is half of the quantum wave of the particle. At time t_1 we look inside box A to see if the particle is there. Immediately after, the situation in box B changes: either the wavefunction of the particle is fully there, i.e the particle is in box B, or the box is empty.

The MWI states that the measurement splits the world into one in which we find the particle in A and another in which we do not. This corresponds to the mixture in box B of a situation without the particle and a situation with the particle. This mixture corresponds to the same local description as before the measurement. Thus, the MWI avoids action at a distance in quantum measurements.

Einstein could not see the proposal for MWI, Everett (1957). Decades after the introduction of MWI, Norsen (2005) does not even mention it in his review of Einstein's boxes argument. Both the claim that MWI has no action at a distance and that other interpretations have it are not universally accepted, see, e.g. Adlam (forthcoming). The lack of consensus is understandable, since it is a very subtle issue. In fact, the example of Einstein's boxes is not enough to show that MWI is the only way to avoid action at a distance because Bohmian mechanics, Bohm (1952), explains Einsten's boxes without action at a distance with one (Bohmian) world. Here I want to carefully define and defend my view on action at a distance in quantum mechanics.

In Section 2 I define the concept of action at a distance. In Section 3 I explain how MWI avoids it. Section 4 analyzes Bohmian mechanics. Section 5 is devoted to the Einstein-Podolsky-Rosen (EPR) and Bell arguments using the Greenberger, Horne, & Zeilinger (1989) (GHZ) setup which shows that we cannot have a deterministic single-world interpretation of quantum mechanics. Section 6 discusses collapse theories with particular attention to the Ghirardi-Rimini-Weber (GRW) flash ontology approach, Tumulka (2006). Section 7 summarizes the results of the paper.

2 Stating the problem

To discuss action at a distance, we need the concept of physical space. I consider the three-dimensional space as given. The notion of action at a distance includes that it is instantaneous. However, in special relativity "instantaneous" is a nontrivial concept. Within special relativity, superluminal action is instantaneous in some Lorentz frame, so the absence of action at a distance is defined as the lack of superluminal action in a Lorentz frame.

To define "superluminal action" we need local events. Then, action at a distance can be defined as a local action that causes a change in a local property at a spacelike remote location. Both the "action event" and the "change of a local property event" require careful discussion. The "action" has to be arbitrary, it has to be "free". It is presented as the result of "free will" action, a very controversial concept. The local change event is also controversial because there is no agreement about the ontology in quantum mechanics and the meaning of the local property, so it is not clear whether the change took place. Essentially, in all interpretations there is no superluminal signaling. Thus, the local change cannot represent the change in locally accessible information. Finally, the concept of "quantum events" is controversial because in most cases there is no rigorous way to define the exact moment when "events" occur.

Let me spell out the paradigm of a physical theory that I propose. Space-time (special relativity) is given. In this space there is some "stuff" which changes in time. This is the ontology of the theory. The stuff might have nonlocal properties (description of which requires reference to several locations), such as entanglement. The amount of stuff and its state are contingent facts, although the theory imposes some constraints, e.g., distributions of charges and fields have to fulfill the Gauss law. These constraints are named physical laws, but the main content of the theory is the laws which govern the time evolution of stuff. (Albert (2015) suggested to consider initial distributions of stuff as a law, but I will not use this semantics.) The theories I will consider have the property that a complete description of stuff everywhere on a spacelike surface, which for simplicity we will take as defined by a moment of time in some Lorenz frame, completely defines what will happen at later times.

In general, "What will happen at later times?" cannot be replaced by "What will the state of stuff be at later times?". In a deterministic theory, the state of stuff specifies the state of stuff later, but many interpretations of quantum mechanics are probabilistic. At any time in the future there will be a well-defined description of stuff, but the present state only specifies a range of possible future states, along with the corresponding probabilities. Note that in probabilistic theories the past states are also not fully specified by the present, but typically we get significantly more information about the past states. Deterministic theories are symmetric with respect to knowledge about the past and future. Complete information about the present provides complete information about all times.

To emphasize, for the types of theories considered here, given complete information about the present, all facts about stuff before the moment we describe add nothing to predict the future behavior. For example, this seems to be in contrast with the Deutsch & Hayden (2000) approach (described in this volume by Bédard (forthcoming) and Kuypers (forthcoming)) in which the future depends not only on the full description of the present, but also on the past. To apply MWI in the Heisenberg representation, they assume a particular initial state.

My paradigm of a physical theory allows us to avoid difficulties with the concept of

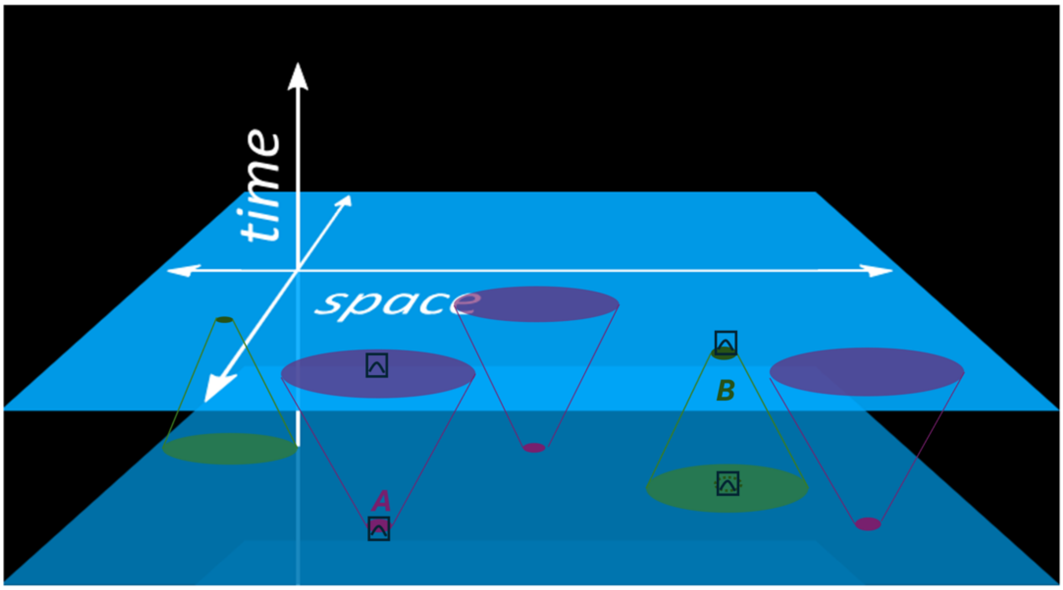

Figure 2: **Action at a distance principle.** We consider universes which at the initial time have the identical descriptions everywhere except for *action regions* described in purple. At later time these universes will have identical descriptions everywhere spacelike separated from the action regions. Conversely, descriptions at a later time in effect regions (green) are fully specified by descriptions in their backward light cones. Einstein's boxes are considered in action region A and in effect region B.

action. To define action, we need to consider the case without action and the case with action. Is one of them counterfactual? In my approach, we can consider these cases symmetrically. I will consider the future of all universes that, at a particular time, have identical descriptions everywhere except for some local regions, the places of actions.

There is no separability in quantum theory: a set of complete local descriptions of stuff at all locations does not provide a complete description of all stuff. Thus, the description of stuff has local properties (which describe every local region), as well as nonlocal properties describing pairs of points (like EPR correlations), triplets of points (like GHZ correlations), etc. The identity of the description of universes at the initial time is related only to points and sets of points which are outside of the action regions (described in purple in Fig. 2). Now we can state the *principle of absence of action at a distance.*

> The universes which at a particular time have different descriptions only at some regions (which we name action regions) at a later time will be indistinguishable everywhere at a spacelike distance from the action regions.

The operational meaning is that any set of measurements at a later time in points which are spacelike separated from the action regions will not allow us to get information about which of the universes we started with. Note that "indistinguishable everywhere" does not mean that we expect the same measurement results for universes which differ in action regions. In probabilistic theories, even if at present two universes are identical, they will not be so later.

My definition of a lack of action at a distance is stronger than the simple requirement that an action in one location will not change any local property at a spacelike separated region. In addition to this requirement, I do not allow "jamming", Grunhaus, Popescu, & Rohrlich (1996), i.e., changing correlations between disjoint regions that are spacelike separated from the action region. In my view, this is what special relativity tells us.

My definition is also (unnecessarily) stronger than the simple approach that a local action cannot cause a change at a space-like separated region. Considering universes with arbitrary differences in separate action regions, I allow nonlocal (and thus nonphysical) actions in action regions, while for an analysis of action at a distance of a theory, it would be enough to consider universes which differ in action regions only due to local operations there. Instead, I assume that even nonlocal operations in action regions cannot lead to changes in spacelike separated regions.

The action at a distance principle can also be expressed in reverse form. Instead of claims about changes in the future caused by local action, we can consider effects in the effect regions where we make observations. Then, the principle of absence of action at a distance is: The description of local regions at a particular time (regions marked in green in Fig. 2) is fully specified by the description in their backward light cones. (Compare my definition with the discussion in Chua & Sebens (forthcoming).)

I find it important to have a general definition of action at a distance which includes sets of actions at several places and to consider the effect of these actions in space-like separated regions. However, the main relevant features can be demonstrated by analyzing the effect of one local action in one local space-like separated region, such as the effect of measurement in one Einstein's box on another. More generally, we model the local action by considering a set of universes with identical descriptions everywhere except for the local region of that action, and a local effect which is specified by a complete local description of the effect region, which operationally provides probabilities for all possible local measurements in this region. Note that these probabilities are considered assuming that we have a complete description of the whole universe. This is why we can consider this local description as an objective property, in contrast to the subjective probability of an agent who has access only to the effect region.

In summary, for a discussion of action at a distance, we need the following concepts.
Space: the three-dimensional space that is postulated and not derived.
Time evolution: from the past to the future.
Local action: modeled by analysis of a set of identical universes at a particular time that are identical everywhere except for some local regions (named action regions) in which the universes have different descriptions.
Local effect: modeled by different descriptions of some local regions (named effect regions) at a later time. The description of the effect regions is the local ontology of these regions that provides probabilities for all possible (local) measurements in these regions. Note that these are not subjective (ignorance) probabilities of agents placed in these regions, the probabilities are based on the total ontological state everywhere at a later time, which might be inaccessible to the local agents.

I suggest narrowing the paradigm of a physical theory that can be characterized by the presence or absence of action at a distance. The paradigm still covers many leading interpretations of quantum theory. However, it directly contradicts the retrocausality approaches of Wharton & Argaman (2020); Aharonov, Cohen, Gruss, & Landsberger (2014); Cramer (1986). The consistent histories approach by Griffiths (1984) and the decoherent histories approach of Gell-Mann & Hartle (1993) involve information from multiple times, so these approaches also do not fit the paradigm. The Context Systems Modality interpretation of Auffèves & Grangier (2016) discusses systems together with context which are, in general, extended in spacetime, avoiding the description of local regions at a particular time, so it is also outside the scope of my analysis. The relational quantum mechanics of Rovelli (1996) and the quantum Bayesian of Caves, Fuchs, & Schack (2002) are not covered because they do not analyze the objective ontology in space. It is not clear for me how to state the question of presence of action at a distance in these theories, although I think that attempts to do so might help to evaluate their significance.

3 Absence of action at a distance in the many-worlds interpretation of quantum mechanics.

As we can learn from a recent conference on this subject, Vaidman (2024), there is a wide variety of versions of the MWI, but it is not controversial to claim that the only ontology of the theory is the universal wavefunction (see, however, Deutsch & Hayden (2000)). All experiences of sentient beings in our and parallel worlds supervene on this highly entangled wavefunction. The most natural approach is to consider the wavefunction of the entire universe as a pure state (see, however, Chen (2021)). If the system we consider is not the whole universe, it might be entangled with some other system(s). The other system might be in the same place, but we are interested in entanglement between systems in separate locations. If there is entanglement of any system in some region with something outside this region, then the complete quantum description according to the standard quantum theory is the density matrix, see §14 in Landau & Lifshitz (2013). The density matrix provides probabilities for the outcomes of all possible sets of measurements in this region.

To demonstrate my claim let us consider Einstein's box A placed in an action region and Einstein's box B in spacelike effect region, see Fig. 2. We arrange the initial state of the particle in Einstein's boxes to be $\frac{1}{\sqrt{2}}(|A\rangle + |B\rangle)$. Let us express it using the Fock states of the boxes

$$\frac{1}{\sqrt{2}}(|1\rangle_A|0\rangle_B + |0\rangle_A|1\rangle_B). \tag{1}$$

Then, the description of the box B is density matrix

$$\rho_B = \frac{1}{2}\left(|0\rangle\langle 0| + |1\rangle\langle 1|\right). \tag{2}$$

In this form, it is clear why, in some sense, we have a half particle in B.

The two universes that we consider to analyze the action at a distance are:
i) Box A is opened and the presence of the particle there is measured.
ii) Box A remains closed.
In the framework of MWI, the local macroscopic measuring device in A is also described by a quantum state. Before measurement, the measuring device is described by the state "ready", $|R\rangle_A^{MD}$. In universe (ii), this state describes the measuring device all the time. In universe (i), the unitary evolution due to the measurement procedure is

$$\frac{1}{\sqrt{2}}|R\rangle_A^{MD}\left(|1\rangle_A|0\rangle_B + |0\rangle_A|1\rangle_B\right) \rightarrow \frac{1}{\sqrt{2}}(|IN\rangle_A^{MD}|1\rangle_A|0\rangle_B + |OUT\rangle_A^{MD}|0\rangle_A|1\rangle_B). \tag{3}$$

The time of action is the time of measurement, so, immediately after the measurement, universe (i) is described by the right-hand side of (3) and universe (ii) is described by the left-hand side of (3). However, in both cases, the description of box B is given by the same density matrix (2). The description of box B in the physical universe (i) includes two worlds created by measurement in a remote location A. In one of the world, the description in B is $|1\rangle$ and in another $|0\rangle$. In every world the description in B has been changed due to measurement in A, but worlds are subjective concepts of observers, so these changes do not manifest a physical change at location B in Nature which includes all the worlds. In the multiverse, the description of B before and after measurement is given by (2).

To put this in a proper context, it is helpful to consider a situation in which there are no changes in B even within the worlds of an observer. Consider "half particle" in A and "half particle" in B without entanglement between A and B. If we consider photons, we can prepare the following state

$$\frac{1}{2}(|1\rangle_A + |0\rangle_A)(|0\rangle_B + |1\rangle_B). \tag{4}$$

Consider again the action, which is a measurement that searches the photon in A. The measurement in A splits the world into two worlds, but now in every world, nothing is changed in B. Box B is described by a pure state $\frac{1}{\sqrt{2}}(|0\rangle_B + |1\rangle_B)$ before the measurement and in every world after the measurement. The probability of finding the particle in B is still half, but the description by a pure state is very different from the description by the density matrix (2). For the pure state, the phase between $|0\rangle_B$ and $|1\rangle_B$ can be measured, while it is not defined in (2).

Note, that the presence of action at a distance in a world is sometimes denied through "local branching", a particular definition of a world which spreads into future light cone of the action event, Wallace (2012). I do not find defining such "worlds" useful, since it is very difficult to construct the physical universe out of such worlds, see the discussion in Ney (forthcoming). In any case, the MWI on the level of the universe, which includes all worlds, has no action at a distance. My second claim is that any single-world interpretation invariably has action at a distance. In the following section, let us start with an analysis of Bohmian mechanics.

4 Bohmian mechanics

The most elegant presentation of Bohmian mechanics is the one adopted by Bell. There is a wavefunction of the universe (the same as in MWI), and, in addition, every particle has a Bohmian position with the guiding equation $\dot{\mathrm{x}} = \frac{\langle j \rangle}{\langle \rho \rangle}$. In my view, a clear way of presenting Bohmian mechanics has to include the postulate that our experience supervenes on Bohmian positions and not on the universal wavefunction.

The positions of Bohmian particles do not affect the wavefunction, so, as in MWI, there are no differences in the local descriptions based on the wavefunction in the regions spacelike separated from the action regions due to differences in these action regions. Note that sometimes, Bohmians take seriously "effective collapsing wavefunction" relevant to observers experiencing their Bohmian position. But this is not a fundamental ontology, since it is derivable from the universal wavefunciton and Bohmian positions. Thus, the only question remains: Do Bohmian positions exhibit action at a distance?

Let us start with an analysis of Einstein's boxes experiment. In addition to the quantum state of the particle (1) we also have the Bohmian position. The guiding equations for Bohmian particles of the measuring device performing the measurement in A depend on the Bohmian position of the particle in Einstein's boxes. They move with the wave corresponding to state $|IN\rangle_A^{MD}$, if the Bohmian position of the particle is in box A,

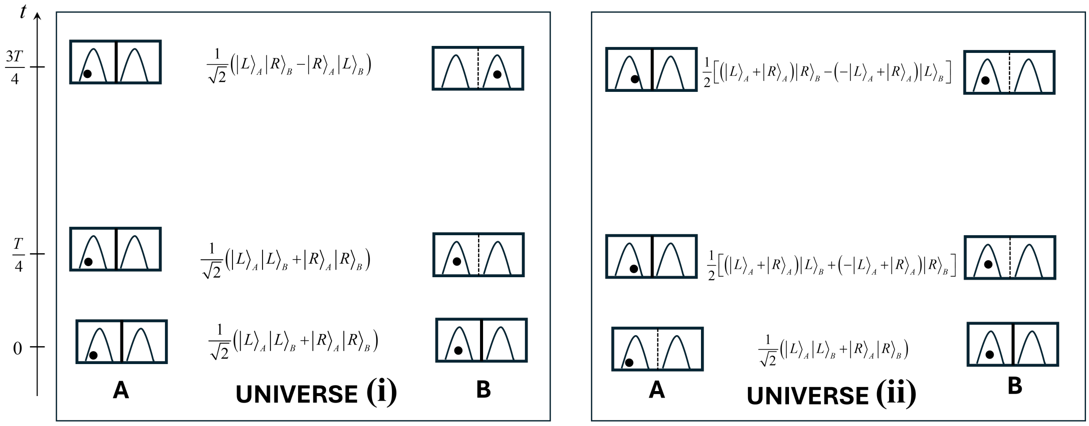

Figure 3: **Action at a distance in Bohmian mechanics.** We start with two identical universes (i) and (ii) which have particle in double box A entangled with a particle in a separate double box B. The action in box A which makes the difference between universes at time $\frac{T}{4}$ is that in universe (i) there is a reflecting wall in box A while in universe (ii) a semitransparent wall. In both cases in box B the reflecting wail is changed to semitransparent wall at $\frac{T}{4}$. The change of the wall in box A during time $[0, \frac{T}{4}]$ causes change in the Bohmian position of the particle B at $\frac{3T}{4}$.

and move differently, corresponding to state $|OUT\rangle_A^{MD}$, if the Bohmian position is in box B. These are changes in A; there are no changes in B depending on the performance (or not performance) of the measurement in A. This shows that Einstein's boxes argument is not enough to make my point. For single-particle theory, we can "complete" the quantum formalism to make it deterministic and without action at a distance fulfilling Einstein's hope.

Let us now consider an example in which Bohmian mechanics exhibits action at a distance. Consider two double boxes, one in A and one in B. Each box has two parts, Left and Right with a wall between them which can be reflecting or semitransparent. When the wall is semitransparent, the wavefunction of the particle oscillates between the boxes with period T. The evolution of the quantum state of the particle during the period is

$$|L\rangle \rightarrow \frac{1}{\sqrt{2}}(|L\rangle + |R\rangle) \rightarrow |R\rangle \rightarrow \frac{1}{\sqrt{2}}(-|L\rangle + |R\rangle) \rightarrow -|L\rangle. \tag{5}$$

We start with entangled particles

$$\frac{1}{\sqrt{2}}(|L\rangle_A|L\rangle_B + |R\rangle_A|R\rangle_B). \tag{6}$$

We consider initial Bohmian positions in the left parts of the boxes, near the left wall, see Fig. 3. To show action at a distance we consider two scenarios. In both cases, for box B we keep the wall closed during the time period $[0, \frac{T}{4}]$ and semitransparent during the time period $[\frac{T}{4}, \frac{3T}{4}]$. In box A there are two cases. In case (i), the wall is closed all the time. In case (ii), the wall is semitransparent during the time period $[0, \frac{T}{4}]$ and then closed. This procedure creates two different universes at time $\frac{T}{4}$, see Fig. 3. In universe (i) the state is still described by (6) and Bohmian positions are near the left wall of the left boxes. In universe (ii) the state is

$$\frac{1}{2}[(|L\rangle_A + |R\rangle_A)|L\rangle_B + (-|L\rangle_A + |R\rangle_A)|R\rangle_B], \tag{7}$$

with the same Bohmian position in B and shifted Bohmian position in A, but still in the left box.

In universe (i), the wave packet of the particle in B starting in the right box is an empty wave due to the Bohmian position of the particle in A, so the Bohmian particle moves with the wave packet from the left box to the right box at time $\frac{3T}{4}$. In universe (ii) the wave packet of the particle in B starting in the right box is an empty wave at $\frac{T}{4}$, but with the evolution it spreads into the left box and the Bohmian position moves to the right box, so the wave packet started in the right part of B plays a role in the guiding equation of particle B. Although $|L\rangle_A$ evolves at $\frac{3T}{4}$ to $|R\rangle_A$, similarly to the effect in "surrealistic" trajectories of Englert, Scully, Süssmann, & Walther (1992), the Bohmian position starting in the left box remains in this box, in contrast to the universe (i). Adding a measurement of the location of the particle with a macroscopic device, left or right part of box B, leads to a macroscopic difference in B depending on action in A.

Note that in Bohmian mechanics, action in A does not lead to immediate change of ontological description in B. At time $\frac{T}{4}$ the density matrix in B in both cases described by (2) and the Bohmian positions are in the same location on the left part. What changed is the local guiding equation, so for a large enough distance between A and B we obtain the superluminal action. The superluminal signaling is avoided by the lack of knowledge of Bohmian positions inside the double boxes at the initial time. Position measurements can give us information about Bohmian positions, but they invariably change the quantum state.

We could construct a simpler scenario that demonstrates action at a distance according to the definition above, i.e., different initial conditions in A lead to different evolution in B. For example, in case (ii) at time $\frac{T}{4}$ we could start with Bohmian particle in A in the right box or in the left box. This would lead to a difference for the Bohmian position of the particle in B at time $\frac{T}{4}$: it will be in the right box instead of the left. However, this change of initial conditions does not correspond to some simple action, so this is why I preferred to present a somewhat more complicated example.

5 Greenberger-Horne-Zeilinger setup, or why we cannot have single-world deterministic theory without action at a distance

In a previous section, I showed that quantum predictions of Einstein's boxes experiments can be explained in a deterministic way without action at a distance in the framework of the Bohmian formalism but that the same formalism exhibits action at a distance in another experiment. We do not have a proof that there cannot be another deterministic single-world theory that completes the standard quantum formalism and provides deterministic predictions for the second experiment. In fact, I see no reason why such a construction cannot be done. However, today we do have an experiment which proves that quantum predictions cannot be explained by a deterministic theory without action at a distance. I will present it using three separate double boxes that I have introduced before, but it is just a translation of the well-known GHZ setup for three spin-half particles of Greenberger et al. (1989).

The double boxes with one particle in every box are located in three separate locations far away from each other, A, B and C. The three particles are in the following entangled state

$$|GHZ\rangle \equiv \frac{1}{2}(|L\rangle_A|L\rangle_B|L\rangle_C - |L\rangle_A|R\rangle_B|R\rangle_C + |R\rangle_A|L\rangle_B|R\rangle_C + |R\rangle_A|R\rangle_B|L\rangle_C). \quad (8)$$

If a box is semitransparent, then from (5) follows that after time $\frac{T}{4}$

$$|+\rangle \equiv \frac{1}{\sqrt{2}}(|L\rangle + |R\rangle) \rightarrow |R\rangle, \qquad |-\rangle \equiv \frac{1}{\sqrt{2}}(|L\rangle - |R\rangle) \rightarrow |L\rangle. \quad (9)$$

Looking at which part of the box, left or right, the particle is present at time $\frac{T}{4}$, is equivalent of measuring of the state of the particle in the basis $|\pm\rangle$ at time 0. Using this basis for two sites, say B and C, the GHZ state will have the following form

$$|GHZ\rangle = \frac{1}{2}(|L\rangle_A|+\rangle_B|-\rangle_C + |L\rangle_A|-\rangle_B|+\rangle_C + |R\rangle_A|+\rangle_B|+\rangle_C - |R\rangle_A|-\rangle_B|-\rangle_C). \quad (10)$$

The GHZ experiment runs as follows. We start with state $|GHZ\rangle$ in three double boxes. The boxes have semitransparent walls, but we decide to replace one of them, or all of them, with fully reflecting walls. We wait time $\frac{T}{4}$ and then measure in which side the particle is present in each box. Essentially, we measure either the L/R basis in every box, or the L/R basis only in one of the boxes and the $+/-$ basis in the other two boxes. We have four possibilities for sets of three local measurements. These procedures involve six possible local measurements, and in the GHZ state there are famously four restrictions for triples of these measurements. If we put reflecting walls in all double boxes measuring every box in the L/R basis then (8) tells us that the only sets of possible outcomes are:

$$\{L_A, L_B, L_C\}, \{L_A, R_B, R_C\}, \{R_A, L_B, R_C\}, \{R_A, R_B, L_C\}. \quad (11)$$

If we chose L/R basis only in A, then sets of possible outcomes are:

$$\{L_A, +_B, -_C\}, \{L_A, -_B, +_C\}, \{R_A, +_B, +_C\}, \{R_A, -_B, -_C\}. \quad (12)$$

Two more constrains are obtained writing the GHZ state with L/R basis only in box B and only in box C. The sets of possible outcomes are:

$$\{+_A, L_B, -_C\}, \{-_A, L_B, +_C\}, \{+_A, R_B, +_C\}, \{-_A, R_B, -_C\}, \quad (13)$$

$$\{+_A, -_B, L_C\}, \{-_A, +_B, L_C\}, \{+_A, +_B, R_C\}, \{-_A, -_B, R_C\}. \quad (14)$$

It is straightforward to see that there is no combination of outcomes of six local measurements, $L/R_A, +/-_A, L/R_B, +/-_B, L/R_C, +/-_C$, which fulfill the four constraints (11-14). For example, $L_A, +_A, L_B, +_B, L_C, -_C$, fulfill (11-13), but do not fulfill (14). (See Vaidman (1999) for a proof of the spin version of the argument.)

The first consequence of this analysis is that we must have randomness. Nature, consistent with quantum predictions, cannot know in advance what the outcomes of some local measurements will be. But randomness is not enough. Immediately after simultaneous measurements in two boxes, the description in the third box has to change. The state was random, i.e., the outcome of some measurement was uncertain before the measurement, but measurements in other boxes made it certain. Note that the assumption of a single world here is crucial. In MWI, there is no uncertainty. In the GHZ scenario every measurement with certainty will have both outcomes. Measurements split the world, or split the observer into worlds which were already created. There is a nonlocal connection between observers in sites A,B, and C, but there is no action at a distance. Local descriptions of sites that describe all worlds together are independent of actions in a spacelike separated region.

6 Collapse theories

When we perform a quantum measurement in which the theory predicts nonvanishing probabilities for various outcomes, we experience obtaining just one single outcome. The quantum formalism with wavefunction is essentially the only formalism explaining experimental data, so many physicists accept the reality of this wavefunction. To avoid a very complicated wavefunction of the MWI and Bohmian mechanics, a collapse to one branch of the MWI wavefunction is frequently introduced. First, there is a formal approach by von Neumann, who postulates the collapse process in quantum measurement and also shows that there is a great freedom in choosing at which stage of the measurement this process takes place. Apart from this, there are physical, but somewhat ad hoc proposals, see Pearle (1976); Ghirardi, Rimini, & Weber (1986) and proposals for collapse related to gravity, Diósi (1987); Penrose (1996). In order to discuss action at a distance in these theories a simple example of Einstein's boxes is enough.

The two universes that we compare are (i) in which a measurement of presence of the particle in box A takes place and (ii) in which it does not. If the wavefunction is ontological, then in box B in case (ii) the description is by the density matrix (2) and in case (i) it is either $|0\rangle_B$ or $|1\rangle_B$. This is action at a distance: without measurement in A, we have an uncertain situation in B. With measurement, the situation is certain. An observer in B cannot distinguish between the two cases, the mixture of presence and absence of the particle is indistinguishable from the quantum description with the density matrix (2). d'Espagnat (2018) coined terms "proper mixture" for the first and "improper mixture" for the second. I find it to be an unfortunate semantics because "improper" mixture is an actual objective physical state, while "proper" mixture is a subjective description of an observer who is ignorant of the complete description of the universe. The local indistinguishability between proper and improper mixtures ensures the impossibility of superluminal signaling in spite of the presence of action at a distance.

Probably due to Bell's insistence to talk about local beables, Bell (1976), a popular approach today is the primitive ontology, see Allori, Goldstein, Tumulka, & Zanghì (2014). The wavefunction spreads out in remote spatial locations, so there is an attempt to avoid considering it as an ontology. In particular, the physical collapse theories started by Pearle (1976) and Ghirardi et al. (1986) were modified to GRW flash theories, Tumulka (2006).

In Einstein's boxes scenario, performing measurement in A does not lead to changes in statistics of flashes in B. Measurement in A leads to two options for flashes there, one corresponding to finding a particle in A and another to not finding it. These two cases, of course, will have different flashes statistics in B. However, comparing the statistics in B in universe (i) in which a measurement in A is performed with universe (ii) in which the measurement in A is not performed corresponds to comparing the combined statistics of finding and not finding the particle in A with the statistics of not measuring in A. This comparison will not show any difference.

However, I find it unsatisfactory to remove ontological status from the wavefunction. In probabilistic theories, the probability that something will happen is physical. So, if we can change the probability of an outcome of local measurement by remote action, it is an action at a distance. In GRW flash theory the wavefunction tells us what the probability of a flash in B is in a particular period of time. Without measurement in A, it is a tiny number. With measurement in A, this number either doubles or becomes vanishingly small. Something physical changed in B. A measurement that tests the presence of the particle in B will have numerous flashes in a particular way if the measurement in A ends up finding one result and different flashes for another. Thus, we get different macroscopic predictions. Again, the local agent in B cannot distinguish (i) and (ii). The mixture of probabilities of two outcomes of universe (i) equals the probability of universe (ii).

Note that action at a distance here is different (one may say weaker) than in the example with double boxes in the framework of Bohmian mechanics, where measurement in A could change the result in B. Bohmian mechanics avoids superluminal signaling in spite of superluminal action by ignorance of the agent about the initial Bohmian position. In the GRW-flash case, we start with reality in B: probability half for finding the particle. By measurement in A, we can change it immediately: to 1 or 0. Superluminal signaling is avoided because of the randomness of the outcome of the measurement in A.

7 Conclusions

The EPR - Bell - GHZ arguments prove that we cannot have deterministic local theory compatible with predictions of quantum theory. In the GHZ scenario, it is not possible that the results of the measurements in three separated locations, L/R and $+/-$, are known before the measurements. Since any of these measurements can be deduced from results of measurements in spacelike separated regions, we know that, in the framework of a single-world theory, a random variable obtains a definite value in a superluminal way. The obtained value cannot be controlled, so for the local observer, it changes an (improper) objective quantum mixture to (proper) subjective mixture based on the ignorance of the results of the remote measurements.

There is no consensus about what ontology should be considered in quantum theory. If the wavefunction is the only ontology, then a single-world interpretation includes collapse which is triggered by local action but makes changes in remote location, so we invariably have action at a distance. In Bohmian mechanics, the wavefunction does not collapse, but when two particles are entangled, action at one location changes the motion of Bohmian particle position in another location, so we again have action at a distance.

In probabilistic theory with local beables such as the GRW-flash approach, action in one location does not change statistics of flashes in another. However, I still argue that there is action at a distance here. Consideration of flashes as the only ontology does not fall into the scientific paradigm according to which at any moment of time the universe has a description. The closest concept based on flashes for a description of the universe at a particular moment is to provide probabilities for flashes at this moment. These probabilities can be superluminally changed.

This argument can be applied more generally than just for analysis of the GRW flashes model. Bell-type arguments lead us to give up the hope of local deterministic descriptions, so, for a single-world theory, the probabilities are real physical quantities. I suggested the concept of “rabit”, a random bit, as a new type of quantum reality, Vaidman (2022). Rabit requires entanglement with an external quantum system and, when measured, rabit disappears. This is action at a distance in probabilistic theories. In the MWI, there are no objective rabits. Measurements split the world with certainty, and all outcomes are actualized in parallel worlds. In Einstein’s boxes the operation in A splits the world to one in which the particle is found and another in which it is not, while in B, the quantum density matrix description remains the same when all worlds are taken into account.

The experience of an observer living in one of the worlds of the Universe in the framework of MWI is identical to the experience of an observer in the universe with corresponding single collapsing world. So, one would expect that within a world of MWI we have the same action at a distance. I argue that it is not so because for action at a distance we need a concept of what will happen in *our* world when we perform a quantum measurement. At least in my version of MWI, Vaidman (2002), this question is illegitimate. The future of my world is a set of worlds. There is no action at a distance because although the sets of worlds created by different actions in one location are different, the descriptions of regions space-like separated from the location of the actions which include all worlds in the sets are identical. There is no way to discuss a single world of my future, only the world of my past. Running the history of my world forward in time, I can easily identify action at a distance. In my memory there are observations of breaking Bell inequalities. But this is not a real feature of the universe, it is a feature of my subjective memory.

In summary, considering the paradigm of a physical theory according to which complete description everywhere at a moment of time tells us what will happen everywhere in the future, the MWI is the only interpretation of quantum mechanics which avoids action at a distance. That is, for universes with differences in the description only in some local regions, the theory makes the same predictions about the future everywhere in space-like distance from these regions. Single-world interpretations of standard quantum mechanics have counterexamples of this principle when a local measurement is performed in an action region entangled with a remote effect region. There are single-world modifications of quantum mechanics like Bohmian mechanics or GRW collapse theory (which, however, often named interpretations) that exhibit action a distance. Finally, there are approaches which do not follow the paradigm of evolution forward in time. It is not clear how to formulate action at a distance principle in these cases.

I feel that the tremendous progress of physics we have achieved until today was made by theories with continuous propagation of particles and fields in space, and this is why I view the principle of absence of action at a distance as so important. This is very strongly related to the fact that today's physics is relativistic, which requires a covariant description. In the MWI, the complete description of local properties of any small spacetime region is the same for all Lorentz observers. Predictions of quantum theory do not allow this feature for single-world interpretation, since Lorentz observers have different descriptions of a spacetime region with a system which was entangled to a remote system measured at a spacelike region.

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