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Decoherence, Locality, and Why dBB Is Actually MWI

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Abstract: In the de Broglie Bohm pilot-wave theory and the many-worlds interpretation, unitary development of the quantum state is universally valid. They differ in that de Broglie and Bohm assumed that there are point particles with positions that evolve in time and that our observations are observations of the particles. The many-worlds interpretation is based on the fact that the quantum state can explain our observations. Both interpretations rely on the decoherence mechanism to explain the disappearance of interference effects at a measurement. From this fact, it is argued that for the pilot-wave theory to work, circumstances must be such that the many-worlds interpretation is a viable alternative. However, if this is the case, the de Broglie–Bohm particles become irrelevant to any observer. They are truly hidden. The violation of locality and the corresponding violation of Lorenz invariance are good reasons to believe that dBB particles do not exist.

Keywords: MWI; pilot-wave; de Broglie–Bohm theory; hidden variables; interpretation of quantum mechanics; locality

1. Introduction

Any data set and mathematical descriptions of data require an interpretation that explains what is happening. von Neumann's set of measurement axioms is an interpretation sufficient for analyzing many physical systems. In the Copenhagen interpretation, these rules are fundamental, as Niels Bohr believed that a realistic interpretation of quantum mechanics was impossible [1] (pp. 76–77). In later years, the Copenhagen interpretation's deficiency has been denoted as "the measurement problem", which signifies the lack of explanation for how the wave function transforms in a measurement (the collapse) and how the outcome is selected. However, the demand for such an explanation is rooted in the expectation that our physical theories will provide a realistic description. Further work to fill this gap has been going on since the conception of quantum mechanics. At the Solvay conference in 1927 [2], Bohm presented his earlier ideas of a combined particle and wave theory combined with Schrödinger's wave theory. It had the potential to be realistic, but de Broglie was dissatisfied with that very aspect of the wave function, which led Bohr to dismiss the possibility of a realistic interpretation. When Bohm [3,4] restated the pilot-wave theory, it got some new, but limited, attention. However, due to Bell's advocacy and the work by Bohm and Hiley [5], as well as Holland [6], the theory has become one of the prominent realistic interpretations of quantum mechanics among philosophers of science [7,8]. Additionally, some physicists also favor this interpretation.

In 1957, Everett [9] asserted that when the observer is treated as a system following the laws of quantum mechanics, the measurement process is fully described by a unitarily evolving "non-collapsing" wave function, just as the processes preceding the measurement are described. Everett's article left many aspects of his proposal requiring further explanation. DeWitt advocated his understanding of Everett's vision in a *Physics Today* article [10]

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and, more importantly, together with his PhD student Graham, published [11] a collection of articles expanding on Everett's original work. Additionally, they denoted Everett's proposal "The Many-Worlds Interpretation". As interest in interpreting quantum mechanics has increased, so has interest in the many-worlds interpretation. This is evidenced by [12], where several proponents and opponents have contributed.

Previously, several articles [13–17] have argued that in the de Broglie–Bohm theory, the particles are somehow irrelevant. The criticisms are based on the fact that both the many-worlds interpretation and the de Broglie–Bohm theory contain the universal wave function, which in the many-worlds interpretation describes the entire universe as a single quantum system. The many-worlds interpretation depicts reality without any point-like particles, but in the de Broglie–Bohm theory, they are fundamental. Several responses have also been provided [18–21] clarifying that the criticisms stem from misunderstandings and questioning the consistency of the many-worlds interpretation. The criticism of the de Broglie–Bohm theory has two major flaws. The articles have relied on a description of the many-worlds interpretation, in which the connection to physical reality remains undefined. The authors have not viewed the de Broglie–Bohm theory in the same way as its proponents do.

The present article takes seriously the view of the de Broglie–Bohm proponents that all matter consists of particles, as well as the grounding of the many-worlds interpretation based on what the wave function signifies. It is argued that there are structures in the wave function that closely resemble what the particles describe, and to such an extent that it becomes undeniable that they represent alternative worlds. It also argued that it is not a viable option to ignore this feature of the de Broglie–Bohm theory, but one has to admit that it renders the particles irrelevant.

The many-worlds interpretation (MWI) will be presented in enough detail to demonstrate its viability and address known concerns in Section 2. In Section 3, the general structure of the de Broglie–Bohm (dBB) theory will be outlined to make clear that it involves not only the same complex decoherence theory but also particle orbits that defy our intuitions about how particles should behave. What are advocated as special methods only available in dBB are shown to either not exist or are not special. In Section 4, the previous arguments and responses are reviewed, and a new argument is formulated. Finally, Section 5 contains the final discussion and conclusions.

2. The Many-Worlds Interpretation (MWI)

Everett analyzed the interaction between the system to be measured, S, and the measurement apparatus, A, as a reaction between two systems,

$$(\sum_i c_i \psi_{Si})\psi_{A0} \rightarrow \sum_i c_i \psi_{Si}\psi_{Ai}, \tag{1}$$

which causes the system and apparatus to become entangled. This analysis was uncontroversial at the time and agrees with London and Bauer [22]. The next step involves the observation of the measurement apparatus by the observer O. The revolutionary step taken by Everett was his assumption that the observer is made up of atoms, which follow the laws of quantum mechanics. Put into mathematical form, we get

$$(\sum_i c_i \psi_{Si}\psi_{Ai})\psi_{O0} \rightarrow \sum_i c_i \psi_{Si}\psi_{Ai}\psi_{Oi}. \tag{2}$$

The final state describes a superposition in which, in each term, the observer has recorded the apparatus value corresponding to the state of the measured system. At first sight, (1) and (2) seem to solve the measurement problem. However, we can mathematically write

(1) using any arbitrary basis for the system S. Surprisingly, Everett did not clearly address this problem, though Mott in 1929 [23] and Bohm in 1951 [24], Chapter 22 Section 11, had given an element to the solution. This partial solution to the basis problem lies in the interaction between the apparatus's degrees of freedom that initially interact with S and the vast number of degrees of freedom of the detector and its surroundings. Currently, this process is referred to as decoherence. In a well-designed detector setup, decoherence will deplete post-measurement interferences between the basis states that the experiment was designed to detect.

Another objection [25] to the physical narrative that Equations (1) and (2) appear to convey is that if the standard measurement axioms are discarded, as Everett argued, then the theory lacks physical substance; it is purely abstract mathematics. Possibly, Everett's view was that his attempt to derive what corresponds to the Born rule would supply the physical connection the theory needed. However, this is a logical mistake. A statement must relate the mathematical entities to the physical reality the theory aims to describe for a mathematical theory to be a physical theory.

What does the wave function represent in the physical world? Not all aspects of the wave function have a well-defined physical significance. For a single particle, the gauge change

$$\psi(x,t) \rightarrow \psi(x,t)\exp(if(x,t)), \tag{3}$$

where x is a point in space and t is the time, changes the wave function, but all measurable quantities remain unchanged. Provided that any appearance of ∇ is replaced by $\nabla - i\nabla f(x,t)$ and the Hamiltonian is transformed according to,

$$\frac{p^2}{2m} + V(x) \rightarrow \frac{(p - \hbar\nabla f(x,t))^2}{2m} + V(x) - \hbar\frac{\partial f(x,t)}{\partial t} \tag{4}$$

the time development of the measurable quantities remains the same. As the field theories of the standard model are gauge theories, there are corresponding transformations in those theories. Only quantities invariant under gauge changes can have significance for what we observe. One such quantity is $\rho(x) = |\psi(x)|^2$. If ρ is non-zero only within a limited volume, we can conclude that the system in question is located in that volume. This conclusion leads us to the following postulate [26]:

EQM 1: *The quantum state: The state is a set of complex functions of positions*

$$\Psi = \{\psi_{k,l}(t, x_1, x_2, \ldots)\} \tag{5}$$

where index l is for gauge components, and k is a composite index for the spin components of all particles. The density gives its basic interpretation

$$\rho_l(t, x_1, x_2, \ldots) = \sum_k |\psi_{k,l}(t, x_1, x_2, \ldots)|^2 \tag{6}$$

answers where the system is in position and spin. It is absolute-square-integrable and normalized to one

$$\int\int \cdots dx_1 dx_2 \cdots \sum_{k,l} |\psi_{k,l}(t, x_1, x_2, \ldots)|^2 = 1. \tag{7}$$

This requirement signifies that the system has to be somewhere, not everywhere.

The quantity ρ is referred to as presence. Vaidman has denoted this quantity "measure of existence" [27], which is similar to the term presence but is more philosophically loaded. The primary purpose of quantum physics is to determine where the systems of interest will be located, such as which detector will be impacted and how the system moves. The latter is described by the currents

$$j_i = \frac{\hbar}{m} \sum_{k,l} \text{Im}[\psi_{k,l}(t, x_1, x_2, \ldots)^* \nabla_i \psi_{k,l}(t, x_1, x_2, \ldots)]. \tag{8}$$

EQM1 gives that a system is more located in regions with a high integrated presence and, correspondingly, it is hardly likely to be located in regions with a minuscule integrated presence. Thus, regions with a minuscule integrated presence can be neglected if we are to obtain an approximate view of a system. The Born rule is derived from where we expect to be located in the future. This approach avoids the usual concept of probability, which may be called "classical probability". As Everett noted [9], in MWI, the probability concept in the Born rule is not a classical probability. We can call this new concept "quantum probability". It relates to statistics and decision-making similarly to how we use classical probability in situations where the outcome is deterministic, but we lack sufficient knowledge to determine what that outcome will be. Wallace [28] presents an alternative derivation of the Born rule, which appears to find physical relevance within a mathematical theory without providing a rule of how mathematics connects to the physical world. Nevertheless, such a rule might be implicit in the numerous explicit assumptions upon which his proof relies. There are too many attempts to derive the Born rule to cover them all here. Refer to [29–31] for discussions on the topic of probability in MWI and MWI in general from perspectives that differ somewhat from those presented above.

The wave function for a system of N particles, $\psi_{jk}(x_1, x_2, \ldots x_N)$, is a function of N positions in three-dimensional space. This structure presents computational challenges and can be conceptually difficult. It was this aspect that led Bohr to conclude that the wave function cannot serve as a description of reality, and that made de Broglie to question his pilot-wave theory. As explained in [32], if we denote the set of all possible configurations of N points in 3-space by $C(N)$, then the wave function is a mapping $C(N) \to \mathbb{C}^p$. It is a mistake to equate $C(N)$ with $\mathbb{R}^{3N}$, as $C(N)$ possesses more structure, such as the distance between two points, $r_{m,n} = |x_m - x_n|$. It is the richness of possible structures of $\psi_{jk}(x_1, x_2, \ldots x_N)$ that allow for entanglement and structures that correspond to several parallel worlds.

In [32], it is shown through gauge invariance that the ontology is represented by the density $\rho(t, x_1, x_2, \ldots) = \sum_{k,j} |\psi_{jk}(t, x_1, x_2, \ldots)|^2$, the associated current(s), and the total spin state, $\chi(t, x_1, x_2, \ldots)$. Both in MWI and dBB, the spatial basis is fundamental, and the density ρ, and the currents j_i are fundamental entities.

2.1. *Absence of Interference Phenomena Involving Macroscopic Objects*

The microscopic objects around us are constantly bombarded by thermal photons, gas molecules, and neutrinos. Consider a gas particle that bounces off a macroscopic object that is in a superposition of two nearby positions, as shown in Figure 1. The quantum states ϕ_A and ϕ_B of the reflected gas particle vary based on the position of the object they reflected off. Assuming only elastic scattering, the absolute value of the scalar product of the reflected quantum states $|\langle\phi_A|\phi_B\rangle|$ represents the remaining coherence between the two locations of the macroscopic object. At large distances, waves from two objects that are half a wavelength apart are different enough that they can be focused at distinct points, implying that $|\langle\phi_A|\phi_B\rangle| \approx 0$. Therefore, once a single particle has scattered, there will be no future interference phenomena between the states of the two positions if they differ by more than half a wavelength. If N particles reflect off the object similarly, the many-particle scalar product is given by,

$$\prod_{i=1}^{N} |\langle \phi_A | \phi_B \rangle_i| \tag{9}$$

which approaches 0 as $N \to \infty$, provided that all $|\langle \phi_A | \phi_B \rangle_i| \le 1 - \epsilon$ for infinitely many i. Coherence can be lost even when the positions differ by much less than a wavelength.

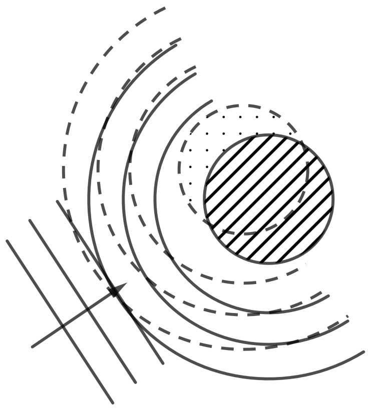

Figure 1. Incoming waves reflect differently depending on where the reflecting object is located.

The above discussion about a macroscopic object in a superposition of two locations sets the stage for the more general case of a macroscopic object in an extended wave function, to which we now turn. We anticipate that coherence will vanish between parts of the wave function that are separated by more than a fraction of the wavelength of the environmental particles. However, competing with the decoherence caused by scattering is the broadening of the wave function due to the center of mass kinetic energy of the macroscopic object. The heavier an object is, the slower the wave function broadens, and the larger the object, the more frequent the collisions will be.

The reduced density matrix describes the state of the macroscopic object,

$$\rho_{\text{Macro}} = \text{Tr}_{\text{Environment}}(|\Psi\rangle\langle\Psi|), \tag{10}$$

where the trace is taken over the particles in the environment that have collided with the object, and Ψ represents the quantum state of both the object and the particles. From the reduced density in the spatial representation, the coherence length can be defined as $l_x = 1/\sqrt{8A}$, where A is given by

$$|\rho_{\text{Macro}}(x - \Delta/2, x + \Delta/2)| \approx \rho_{\text{Macro}}(x, x) \exp(-A\Delta^2). \tag{11}$$

For a macroscopic body with mass m that has become in equilibrium with the surrounding gas of particles at temperature T, the coherence length is

$$l_x = \frac{h}{\sqrt{2mk_B T}}. \tag{12}$$

Joos and Zeh [33] conducted the first detailed investigation into these aspects of decoherence. For a comprehensive review of decoherence theory, refer to [34].

If the recoil of the macroscopic object is neglected and we assume that it is subject to the potential energy $V(x)$, then the time dependence of the reduced density matrix is given by

$$i\hbar \frac{\partial \rho(x, x', t)}{\partial t} = \left[\frac{\hbar^2}{2m} \left(\frac{\partial^2}{\partial x'^2} - \frac{\partial^2}{\partial x^2} \right) + V(x) - V(x') - i\Lambda(x - x')^2 \right] \rho(x, x', t), \tag{13}$$

where Λ is a parameter for the rate of decoherence from the scattering of the surrounding particles. Caldeira and Leggett [35] included recoil, which led to an additional friction term. Such dissipation additionally implies Brownian-motion-type fluctuations.

If there are N macroscopic bodies located in a gas of particles that scatter off them, the reduced density matrix that applies to all of them is in the following form,

$$\rho_{\text{Macros}}(x_1, \ldots, x_N, x'_1, \ldots, x'_N). \tag{14}$$

Decoherence then gives that ρ_{Macros} quickly becomes small as the values of $|x_1 - x'_1|, \ldots, |x_N - x'_N|$ increase.

The fact that the spatial coherence length never reaches zero implies that the reduced density matrix never becomes diagonal in the spatial basis. Joos and Zeh [33] determined that the states that diagonalize the density matrix are spatially very extended. These eigenstates possess the characteristic that if the system ceases to interact with the environment, the evolution of the eigenstates is governed by the Schrödinger equation for the system. Stapp [36] assumed that the eigenstates correspond to the state of the macroscopic system in the branches. He used the fact that the eigenstates are not localized to argue that the universal wave function fails to reproduce our observations.

Decoherence theory alone cannot define the branch structure that MWI is based upon. The interactions that macroscopic bodies have with each other happen through the emission and reflection of particles and by direct contact. In this way, they measure each other's positions. Equation (14) defines an ensemble of worlds or branche of macroscopic objects with very narrow quantum uncertainties. The interactions between the macroscopic bodies will keep these branches intact. Only under exceptional situations will these interactions cause substantial splitting of a branch. The time development of macroscopic objects' positions defines a continuous evolution of each branch.

By assuming that the evolution of the macroscopic is influenced, except for the gases causing decoherence, by a slowly varying potential $V(x_1, x_2, \ldots)$ we can proceed as with Ehrenfest's theorem. Any expectation value for the system can be calculated from the reduced density matrix $\langle Y \rangle = Tr(\rho_{\text{reduced}} Y)$. With that, Equation (13) gives

$$\frac{d}{dt}\langle x_i \rangle = \frac{\langle p_i \rangle}{m}, \quad \frac{d}{dt}\langle p_i \rangle = -\langle \nabla_i V \rangle. \tag{15}$$

The expectation value is for the "universal" wave function, thus an average over all branches. If we single out one of them, the dispersions will be narrow not only for positions but also for the momenta, as the continuous "measurements" by the environments will separate into branches with small dispersions in the velocities. Thus, we get

$$\frac{d}{dt} x_i^{(\text{cl})} \approx \frac{p_i^{(\text{cl})}}{m}, \quad \frac{d}{dt} p_i^{(\text{cl})} \approx -\nabla_i V^{(\text{cl})} \tag{16}$$

where $x_i^{(\text{cl})} = \langle x_i \rangle_{\text{branch}}$, $p_i^{(\text{cl})} = \langle p_i \rangle_{\text{branch}}$, and $V^{(\text{cl})} = \langle V \rangle_{\text{branch}}$. The macroscopic objects move within each branch, very similarly to what Newton's equations of motion give.

Sudarsky and coworkers [37,38] have argued that decoherence cannot give rise to a loss of symmetry and thus cannot explain the granularity of the universe we observe. They argue that a theory like dBB is needed to account for our observations. Their point is that if the initial state has a symmetry and the equations of motion commute with the symmetry operators, then all future states will also have the symmetry. This is perfectly correct, but it does not negate the fact that a symmetric quantum state can describe many branches, almost all of which are asymmetric. The multitude of branches that decoherence creates manifests in correlations between macroscopic objects at different times,

$$\langle\Psi(t)|P(x_2,p_2)exp(-iHt/\hbar)P(x_1,p_1)|\Psi(0)\rangle, \tag{17}$$

where $P(x,p)$ is a projection operator onto a Gaussian state with average position x of the center of mass, average momentum p, and a suitable width. These correlations are related to the classical motion discussed in the previous section.

The "breaking of symmetry" here is akin to the spontaneous symmetry breaking known from condensed matter physics and relativistic quantum field theories, which can be defined by the appropriate correlations.

2.2. The Freedom of Basis Choice

The Hilbert space analysis introduced by von Neumann [39] has shown that the wave function can be viewed as a member in a vector space and that any basis in that vector space is legitimate. In the Copenhagen interpretation, operators and their eigenfunctions have an ontological character due to their appearance in the measurement postulates. In MWI, the fact that the universal wave function belongs to a Hilbert space only implies that a large set of transformations are available due that the wave function is normalizable. Any Hilbert space analysis application must start from one fundamental representation. In the case of non-relativistic quantum mechanics, that is, the Schrödinger equation, it is the spatial and spin representation. It is also the case that positional basis is fundamental in relativistic QFT. Expressing the wave function on another basis should be viewed as a transformation, like a Fourier transformation. Which basis to use depends on what best presents the relevant features. The freedom to choose a basis creates the possibility of deceptive basis choices. For example, the entangled wave function of a system S and measurement apparatus M may be written in more than one way,

$$\sum_i |x_i\rangle_S|A_i\rangle_M = \sum_j |y_j\rangle_S|B_j\rangle_M. \tag{18}$$

The first version seems to say that property x is measured and represented by property A of the apparatus, while in the latter, it is y and B, respectively. However, this interpretation of that state is erroneous. As the equality tells us, this is the same state transformed in two different ways. None of the expressions might have anything to do with what is measured. What is measured is entirely given by the property of S the measurement system gives a local macroscopical manifestation. If there is a quantum uncertainty in that property, the measurement will produce a branching into new branches of the kind discussed above.

Is an Explicit Declaration of a Preferred Basis Necessary?

When Hemmo and Shenker [40] claim that something must be added to the formulation of the many-worlds interpretation, they consider the following formulation of the MWI:

1. The complete physical state of the universeat any time t (in all its details) is given by a vector in the Hilbert space associated with the universe.
2. The time evolution of this universal state is given by a linear and unitary equation (the Schrödinger equation in the non-relativistic case).

They state that even if it is the case, it is the combination of the Hamiltonian and the features of humans that "determine which basis appears in our experience... due to that it has some special features... goes beyond 1 and 2", this fact has to be added to the statements that define the theory.

However, when they discuss the view of observations by humans confined to a particular *xi*-basis (the spatial basis in the present theory) and that the decoherence theory shows the appearance of a classical world for that basis, they state "It seems to us that this claim may require adding a new principle that would rule the *xi*-states as real, or something similar. But we are not sure".

Hemmo and Schenker are right in that something concerning basis is missing in some descriptions of how decoherence gives rise to branching, for example, in Wallace's accounts [29,41]. There has to be a fundamental basis from which any quantum mechanical description starts. According to EQM1, the fundamental basis is the spatial and spin basis. All emergent structures, macroscopic bodies, decoherence, humans, measurement processes, etc., have their fundamental description on that basis. The choice of basis is a choice of language for describing a state or a process.

Hemmo and Schenker argue that a well-defined rule is necessary to define the highest amount of coherence between structures at which that they are different branches. But what the limit is depends on the circumstances. If the amplitude of one of the basis states we try to measure is very low, we might be unable to detect it as noise in detectors and electronics might hide it. This tells us that thresholds for what can be a branch are related to "practical" questions of observability.

2.3. Locality

The EPR article [42] and later Bell's theorem [43] have raised the question of locality in quantum mechanics. Bell proved that realistic quantum mechanical interpretations that impose that there is a single outcome from experiments, as in the Copenhagen interpretation (CI) or dBB theory, either include or imply an instantaneous interaction at a distance, or are superdeterministic. As there is not a single outcome in the many-worlds interpretation when measuring a system with many potential outcomes, the theorem does not apply. Moreover, the many-worlds interpretation is extended to the relativistic realm by replacing non-relativistic quantum mechanics with relativistic quantum field theories, which are local. The many-worlds interpretation of QFT is a local causal theory in the following sense. Take a (small) region in space and denote by L its surface in space-time at time T_L, see Figure 2. Consider the reduced density matrix ρ_L that describes the quantum state at L and the backward light cone of L. All gauge invariant features of ρ_L only depend on the structures inside the backward light cone. For example, those features of ρ_L are given by the reduced density matrix ρ_C at cut C, but any process that happens outside the light cone will not affect ρ_L.

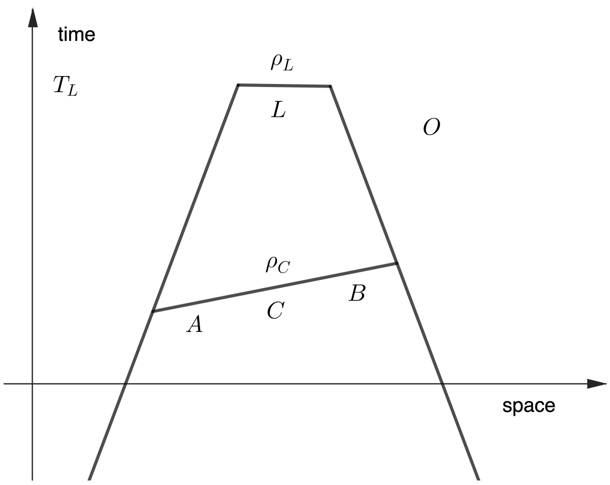

Figure 2. Backward light cone from small region at time T_L. The quantum state at the region is given by the density matrix ρ_L. There is a cut C through the light cone, with quantum state ρ_C. The letters A, B, and O represent small regions in space-time.

Suppose an entangled pair of particles is produced inside the light cone. One of the particles is measured at L and the other at space-time region O. The measurement at O will not at all affect ρ_L and thus not affect the outcome of the measurement there. Likewise, if there is another pair of entangled particles measured at point A and B, respectively.Here too, the measurement at A in no way influences what happens at B, and vice versa, but those measurement processes affect ρ_L, where the correlations between the measurement results due to the entanglement will be encoded.

Bell [44] (reproduced in [45]) has argued that our relativistic quantum field theories are not local, but he was then implicitly assuming CI or some other "one-world" interpretation. In the case of the CI, the description from "preparation" up to the measurement is described by local processes and propagations limited by the speed of light. The CI description of measurements implies highly non-local effects, as Norsen's [46] discussion of Einstein boxes clearly shows. The appearance of non-locality in dBB theory is discussed in Section 3.

As the formulation of an interpretation of quantum mechanics can imply non-locality, we must address whether the formulation of MWI implies a non-locality. That is, is there an instantaneous change at a distance of the ontological entities? We have already seen that that is not the case. What about the creation of branches? Can that somehow imply a non-locality? The answer is no. The branch structure is a phenomenon that emerges out of local interactions and relativistic propagation. For example, when a measurement causes branching, the decoherence is initially confined to inside the detector and its adjacent environment. It then spreads outwards, no faster than the speed of light. Wallace [29] has illustrated this process for the case of measurements on a pair of entangled particles.

General statements claiming that quantum mechanics is non-local are inaccurate. According to Bell's theorem, theories that entail a single outcome at measurements are either non-local or superdeterministic. However, Bell's theorem is not concerned with many-world interpretations. Thus, it can not imply a general statement about quantum mechanics.

3. De Broglie–Bohm Pilot-Wave Theory

The de Broglie–Bohm theory [21] starts from the universal wave function described by the Schrödinger equation,

$$i\hbar\frac{\partial\Psi(\overline{x},t)}{\partial t} = -\sum_i \frac{\hbar^2}{2m_i}\nabla_i^2\Psi(\overline{x},t) + V(\overline{x})\Psi(\overline{x},t), \tag{19}$$

where $\overline{x} = x_1, \ldots, x_N$. Another key aspect is the presence of a set of point particles, referred to as B-particles. Their equation of motion is expressed as

$$\frac{dX_i}{dt} = \frac{j_i(\overline{X})}{\rho(\overline{X})} \tag{20}$$

where $X_i(t)$ denotes the position of B-particle i, j_i represents the quantum mechanical current of particle i summed over spins, $\overline{X} = X_1, \ldots, X_N$, and ρ is the absolute square of the universal wave function summed over spins. The ontology comprises the B-particles (sometimes called the primary ontology) and the wave function, which guides the B-particles according to (20). The wave function is sometimes argued to be nomic [47], a law of nature that acts on the particles. This classification appears to be somewhat of a stretch, considering its dynamic and contingent nature. Nonetheless, what is nomic is also ontic.

The B-particles are the constituents of matter. The wave function serves to guide them, much like a new kind of force. As Bell [48] stated, the wave function represents the hidden degrees of freedom, while the B-particles are the visible ones. The locations of the particles are determined when an agent observes how matter is arranged in its environment. According to Equation (20), the velocity of one B-particle depends on the positions of the others, even if they are very far away. Here, we have an instantaneous interaction between B-particles at different locations. This non-locality is a fundamental aspect of the pilot-wave theory.

Bohm [4] took his previous analysis of the measurement process as a decohering process and added the B-particles. He considered how changes in the measurement apparatus's many "thermodynamic" degrees of freedom led him to conclude that "we can ignore the possibility that it [interference effects] will ever occur". All B-particles end up in one of the 'branches' of the many-worlds theory and most probably stay there.

The initial location of the B-particles before a measurement is decisive for where they end up, which decides the measurement value. Given the Born rule, one might take the probability of their positions as $\rho(\overline{X})$, which has been named the equilibrium distribution. It has the property—equivariance—that if it is true at one time, it is also true at any later time.

Assuming the equilibrium distribution, Dürr et al. [49] derived the Born rule for the effective wave function, which posits that the universal wave function satisfies

$$\Psi(\overline{x},\overline{y}) = \psi_e(\overline{X})\Phi(\overline{y}) + \Psi^{\perp}(\overline{x},\overline{y}), \tag{21}$$

where it is assumed that Φ and $\Psi^{\perp}$ have "macroscopically" disjoint $\overline{y}$-support and that the B-particle coordinates $\overline{Y}$ related to the $\overline{y}$-coordinates are located within the support of Φ, rendering $\Psi^{\perp}$ irrelevant. This is to say that the B-particles are in a branch of the universal wave function given by $\psi_e(\overline{x})\Phi(\overline{y})$. The effective wave function is $\psi_e(\overline{x})$, and the separable structure of the branch is intended to describe an idealized measurement situation. If the B-particles are located in such a branch, then the probability distribution can be updated to $\psi_e(\overline{X})\Phi(\overline{Y})|^2$. Dürr et al. were concerned about the complications arising from previous measurements that accumulate knowledge about B-particles. Based on Bohm's analysis, we can conclude that a measurement prompts an update of the probability distribution of B-particles to the absolute square of the branch wave function whenever it can be defined.

The concept of the conditional wave function is useful here. The variables of the universal wave function are divided into two sets, the $\overline{x}$ and $\overline{y}$. The coordinates of the B-particle coordinates $\overline{Y}$, associated with $\overline{y}$, are assumed to be known. The conditional wave function [49] is defined as $\psi_c(\overline{x},t) = \Psi(\overline{x},\overline{Y},t)$. Assuming that $\overline{Y(t)}$ are known, it can be viewed as the pilot wave for the unknown coordinates $\overline{X}$. We can assume that $\overline{Y}$ provides the positions of the macroscopic objects, while $\overline{X}$ relates to the microscopic degrees of freedom. From the equilibrium distribution, we can derive the conditional probability, which amounts to the probability distribution for $\overline{X}$ is $P(\overline{X},t) = |\psi_c(\overline{X},t)|^2$. In principle, the coordinates $\overline{Y}$ cannot be considered as perfectly known. An appropriate average of the positions over the corresponding decoherence lengths must be included,

$$P(\overline{X},t) = \int |\Psi(\overline{X},\overline{Y},t)|^2 f(\overline{Y},t)d\overline{Y}, \tag{22}$$

where $f(\overline{Y},t)$ is the probability of the $\overline{Y}$ coordinates and $d\overline{Y}$ is a "volume" measure. The function f has to be chosen such that P becomes normalized. This is simply the Born rule applied to the universal wave function, modified by the function f to account for what we know. Equation (22) is equally relevant in MWI for a branch where certain objects with variables $\overline{y}$ are localized as given by the function $f(\overline{y})$. Between measurements, the equivariance guarantees that within the branch, the conditional equilibrium distribution $|\Psi(\overline{X},\overline{Y},t)|^2 f(\overline{Y},t)$ remains valid.

The question of how a (sub)system can contain information about events that have occurred was addressed by Stone [50]. He claimed that the B-particle configurations "cannot store any information at all" beyond what the wave function provides. However, Stone is unclear on how information is contained within the wave function. Maudlin [51] responded that when a measurement is performed, the B-particles of the measurement apparatus will move into a configuration depending on the position of the measured B-particle. Consequently, the positions of the apparatus B-particles contain information about the position of the measured B-particle. A set of B-particles will be located in positions that reflect what occurred during the measurement. However, as established in the previous paragraph, we know that the information B-particles encode about the location of other B-particles cannot be more precise than what the wave function and our knowledge of macroscopic objects allows.

Valentini [52] has pursued the potential of the non-equilibrium probability distribution of B-particles. He [53] recently argued that non-unitary corrections to semi-classical quantum gravity could result in a non-equilibrium distribution. This argument is not convincing, as omitted degrees of freedom and truncated expansions usually lead to spurious non-unitarity. Valentini has suggested that a non-equilibrium distribution could allow for more precise measurements of the position of B-particles than what the Born rule permits, which he refers to as sub-quantum measurements. Thus far, there is no evidence supporting non-equilibrium B-particle probability distributions.

3.1. The Lesson from Interferometry

Although dBB is primarily a theory of particles instead of waves, it can accurately reproduce interference phenomena because the wave function pilots the particles, and the Born rule provides the probability of where the particle will end up in the detection system. A celebrated example is the double-slit experiment [54]. The movement of the B-particle differs from what one might expect based on wave theory. In a perfectly symmetric double-slit experiment, all B-particles passing through the left slit will land on the left side of the detector screen. This phenomenon is explained by the non-crossing rule of the B-particle's different paths and by the fact that the system is effectively two-dimensional. In a system consisting of a single particle, which is the case here, the velocity at a specific point in three-dimensional space is determined by the wave function at that point, making it a unique vector. If two paths could intersect, there would need to be two different velocity vectors at the intersection point, thus violating uniqueness. In two dimensions, two trajectories cannot switch sides due to the non-crossing rule, but in higher dimensions, they can pass around each other. The non-crossing rule also gives rise to surprising effects in other interference experiments.

Figure 3 shows an incomplete Mach–Zehnder particle interferometer. The original beam is split into two beams that are then reflected, causing the beams to cross. At this point, there is no second beam-splitter present, which allows the waves to intersect. Due to the non-crossing rule, the B-particles will shift from leg I to a and from II to b.

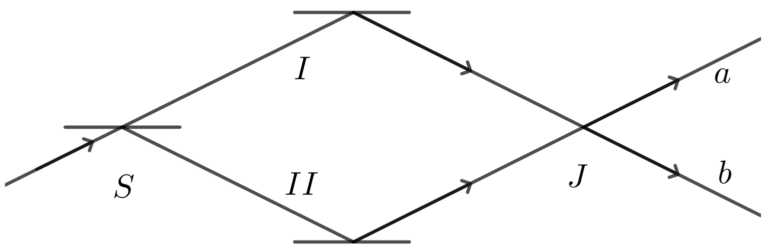

Figure 3. An incomplete Mach–Zehnder particle interferometer: the incoming wave is split at S into paths I and II and is deflected to meet at J.

Englert et al. [55] considered having "which-way" detectors in the two legs of the interferometer. The detectors are microscopic in the sense that there is only a single degree of freedom that is affected at the detection. The wave function description of the state after the crossing is then

$$w_I \psi_b + w_{II} \psi_a, \tag{23}$$

where ψ_a and ψ_b is a wave packet in beam a and beam b, respectively, and w_I and w_{II} is the state of the which-way detectors in which they have detected passage at leg I or II. The wave function, together with the Born rule, implies that whenever the detector at leg I reacts, the particle will be found at b, and when the detector at leg II reacts, the particle will be found at a. Detailed calculations of the motion of the B-particles, including those in the detectors, gave rise to the surprise that though some trajectories now go straightforward in the crossing J, from I to b and from II to a, some still will turn from II to b and from I to a. Thus, occasionally, the B-particle has passed through leg I, but the detector at leg II reacted or passed through II, and the detector at I reacted. The reason this can happen is the no-locality of the dBB theory.

Englert et al. argued that dBB theory should be considered "surrealistic" rather than "realistic". In defense of dBB theory, Dürr et al. [56] contended that any discussion of which path the system took must be based on a "proper framework". They noted

> the "utter meaningless" ness of the question about which "slit" the atom went through can, within the framework of orthodox quantum theory, in no way be avoided through the use of "one-bit detectors"—however they are called!

The dBB theory makes the same predictions as standard quantum mechanics, so it is not surprising that quantum mechanics surprises us. Englert et al. [57] replied that "It is quite unnecessary, and indeed dangerous, to attribute any additional 'real' meaning to the ψ-function" while still advocating their own interpretation of which way the particle went. Dewdney et al. [58] defended the dBB theory and clarified that a detector with few degrees of freedom can be fooled. See [59] and the sources cited therein for further discussion on the topic of B-particles in interferometers.

It turns out that the more degrees of freedom are active in the which-way detector, the more accurate the detection becomes. In other words, to obtain a reliable measurement, the detector must produce decoherence. The discussion of "surreal trajectories" highlights this important fact. The possibility of fooling the detector corresponds to the possibility of regaining coherence. dBB theory aligns with the standard interpretation and MWI concerning what we can observe. Therefore, the "surrealistic" trajectories in interferometers reveal a general feature of quantum mechanics. The set of all possible B-particle trajectories gives how the currents "flow".

3.2. Non-Locality and Relativity

The measurement of a Bell pair is a case where the dBB theory displays its non-locality most clearly. The measurement of one of the particles gets its B-particle to move to reflect the result. The equations of motion (20) for the other particle in the pair show that its motion will now be affected by the measurement of the first particle. The distance between the two particles can be arbitrarily large. Thus, the non-local influences can act at any distance, seemingly violating relativity. Maudlin [60] introduced a foliation in space-time in which the equation of motion is defined. In this way, the theory becomes well-defined but at the cost of an explicit violation of relativity in the formulation of the theory.

3.3. The Calculations of B-Particle Trajectories

Are there calculational methods available in dBB theory but not present in other interpretations of quantum mechanics, and are there methods not available in dBB? Dürr et al. [49] claimed that the conditional wave function is only available due to the existence of B-particles, and Bell [61] argued that the reduced density matrix is not suitable for dBB theory.

The conditional wave function $\psi_c(\overline{x},t) = \Psi(\overline{x},\overline{Y},t)$ involves dividing the "universe" into a subsystem and its environment, with variables $\overline{x}$ and $\overline{y}$, respectively. The coordinates $\overline{Y}$ of the environment B-particles are assumed to be known. Nonetheless, the premise that certain coordinates are perfectly known contradicts the description of measurements in dBB theory. Any measurement will lead to the B-particle positions being within the relevant branch and probabilities as specified in (22), or similarly for $\overline{Y}$. The certainty or uncertainty regarding the position of objects does not depend on whether one supports dBB, MWI, or orthodox quantum theory. In reality, conditional wave functions or effective wave functions provide no advantage for physicists who adhere to dBB, because when considering the uncertainties of the B-particle positions, the available calculations remain the same regardless of interpretation. First, consider that the $\overline{Y}$-coordinates are completely unknown. To estimate the path of $\overline{X}$, one can average over $\overline{Y}$. This yields the average density $\langle\rho(\overline{x},t)\rangle$ and current $\langle j(\overline{x},t)\rangle$,

$$\langle\rho(\overline{x},t)\rangle = \int \Psi(\overline{x},\overline{Y},t)^*\Psi(\overline{x},\overline{Y},t)d\overline{Y} = \rho_{\text{redu}}(\overline{x},\overline{x},t), \tag{24}$$

$$\langle j_i(\overline{x},t)\rangle = \frac{\hbar}{m}\int \text{Im}\big[\Psi(\overline{x},\overline{Y},t)^*\nabla_i\Psi(\overline{x},\overline{Y},t)\big]d\overline{Y} = \frac{\hbar}{m}\text{Im}\nabla_i\rho_{\text{redu}}(\overline{x},\overline{x}',t)|_{\overline{x}'=\overline{x}}, \tag{25}$$

where ρ_{redu} is the reduced density matrix. If certain Y coordinates are approximately known, we are in a branch where the full universal wave function is not entirely applicable. As discussed in the context of probabilities (22), this knowledge corresponds to a weight function $f(\overline{Y},t)$. The reduced density matrix

$$\rho(\overline{x},\overline{x}',t)_{\text{redu}\backslash\text{f}} = \int \Psi(\overline{x}',\overline{Y},t)^*\Psi(\overline{x},\overline{Y},t)f(\overline{Y},t)d\overline{Y} \tag{26}$$

can be employed to calculate the average density $\langle\rho(\overline{x})\rangle$ and current $\langle j(\overline{x})\rangle$. We have seen that, in practice, the use of conditional wave function amounts to employing the reduced density matrix in one way or another. Therefore, we can conclude that the conditional wave function does not provide any advantage over the reduced density matrix, and the reduced density matrix is a useful method within dBB theory.

This shows that the results from decoherence theory can be directly applied to dBB theory without needing to calculate B-particle trajectories explicitly. The dispersion in the trajectories can be controlled by considering the known knowledge, reducing the uncertainties to those of a single branch. This directly leads to the classical Newtonian motion as given in (16). Appleby [62] has made a commendable effort to calculate the behavior of B-particles in decohering systems that extend beyond the description provided here. It is difficult to understand with what knowledge about the motion of B-particles in macroscopic bodies such a calculation could contribute, considering that the standard decoherence theory applies to dBB theory as well.

To explain how classical behavior emerges, Goldstein [21] refers to the work of Allori et al. [63] in the 2021 version of his review of dBB theory. They support their study of B-particle motion with the incorrect assertion that "quantum mechanics does not contain the means for describing the classical world in any approximate sense, and one needs to go beyond quantum mechanics in order to do so". For the most part, the article is concerned with the motion of the B-particle in a wave packet subject to an external potential. They only have a marginal discussion of decoherence, without a proper quantitive discussion of its effects. There can be no realistic discussion of classicality using single-particle wave packets while ignoring interactions with the environment.

Rosaler [64] performs a decoherence-based analysis of classicality and finds that it "falls out almost trivially from results developed in the context of decoherence theory". However, Rosaler argues that "classicality in Bohm's theory requires not just the orthogonality of environmental states associated with different branches", but the stronger condition of disjointness of the support similar to that in the definition of the effective wave function. Romano [65] also uses such a condition. Their condition is unnecessarily restrictive, rendering their analysis seemingly less valid than the standard theory, which, as stated above, applies to dBB theory.

3.4. Critique of the Particle Ontology

In scattering and other 'streaming' situations, B-particle motion provides a clear explanation of the events that occur. However, this is far from true for the bound stationary states. In a harmonic oscillator or a particle in a box, the B-particle stands still, independent of how high the energy is. These are situations where the intuition we receive from classical physics is of a system in more or less intense motion, but the B-particle tells the opposite story. If we look at the electron in the hydrogen atom and neglect spin–orbit coupling, whether the B-particle will circle around or stand still depends on the choice of eigenstate, as Pauli commented already at the 1927 Solvay conference [2].

The manifest image of the material world around us is not that of infinitely small particles. Desks, chairs, books, water in streams, etc., appear to consist of something continuous. In Newtonian mechanics, point particles were a mathematical fiction. Still, in 1904, it was reasonable to consider continuous matter distributions as evident from the model of the atom Thomson suggested. The very small particle we call electrons was discovered in 1897. In 1925 and 1926, respectively, Heisenberg and Schrödinger abolished the classical particle concept. An ontology that identifies solid matter as point particles separated by an invisible 'force', not affected by the particles, is far from a natural ontology. The argument that the B-particle ontology is the right kind of thing is weak.

3.5. dBB Summary

dBB provides a realistic depiction of quantum phenomena where B-particles serve as the fundamental building blocks of matter. The theory avoids the measurement problem as it describes measurements as physical processes following the same laws as any other process. The claims that dBB theory has access to methods unavailable in MWI and that the standard interpretations are mistaken. Since the B-particle trajectories are the flow lines provided by the current, and the calculation of flow lines enhances knowledge of the quantum state, the computation of trajectories contributes to our understanding of quantum phenomena. Thus, it is a mistake to claim that the trajectories, that is, the flow lines, are an exclusive feature of dBB. That calculations are performed to reformulate in dBB language what is already understood through conventional methods without adding new insights to the general question seems to be an unfortunate consequence of the unwarranted belief that the dBB theory differs more from other interpretations than it actually does. The B-particle aspect may appear appealing since it offers a one-world interpretation of quantum mechanics; however, the cost is nonlocality and a resulting violation of relativity. The particle component of the ontology diverges significantly from the manifest image and lacks explanatory strength.

4. Is dBB MWI?

The increased understanding of MWI over the last few decades has made it clear to its proponents that it is the only interpretation of quantum mechanics that fully aligns with the Schrödinger equation and experimentally realistic relativistic QFT without unnecessary extras. The following quote from Deutsch [13] illustrates this sentiment.

> The objection is that we have confused an uncontroversial physical theory, quantum theory, with its controversial parallel-universes 'interpretation' for which (as for any interpretation) there could not possibly be any experimental evidence. Thus we could be accused of appealing to the authority of a scientific theory to justify an optional metaphysical overlay which philosophers and physicists are surely entitled to resist, or indeed to reject out of hand if it suits them. But there is a false assumption behind this objection: the assumption that there is more than one interpretation of quantum theory.

The proponents of the dBB theory may argue that their alternative interpretation is entirely acceptable, if not the only valid interpretation. However, Deutsch formulated the provocative thesis: "pilot-wave theories are parallel-universe theories in a state of chronic denial". He describes the dBB theory as a wave function with both occupied and unoccupied grooves that interact with one another. In short, he makes the following conclusion:

> Pilot-wave theories assume that the quantum formalism describes reality. The multiplicity of reality is a direct consequence of any such theory.

Zeh [14] responded to Goldstein's advocacy of dBB in Physics Today [66,67] with a similar criticism of dBB as Deutsch. Additionally, Zeh pushed the importance of decoherence for both dBB and MWI.

Wallace [15] argues from an analysis of MWI based on decoherence theory. His argumentation was quite short:

> to predict the behavior of the corpuscles [B-particles] we have to predict the behavior of the wave function, and to predict the behavior of the wave function we have to study the emergent patterns within it. Thus cats and all other macro-objects can be identified in the structure of the wave function just as in the structure of the corpuscles. But the patterns which define them are present even in those parts of the wave function which are very remote from the corpuscles. So if we accept a structural characterization of macroscopic reality, we must accept the multiplicity of that reality in the de Broglie–Bohm pilot wave as much as in the Everettian universal state.

Brown and Wallace [16] sought to improve upon this and Deutsch's argumentation. They argue that Bohm's intentions have been misinterpreted. In their view, Bohm's goal was not to solve the measurement problem. They first focus on Bohm's description of the measurement process, in which he showed that the B-particles move so that one can identify the outcome with their positions—"The Result Assumption". In their view, the B-particles only serve to select this specific branch. Brown and Wallace then conclude that the wave function is more important than the B-particles. They also conclude that dBB is ontologically excessive compared to MWI. The decoherence theory's successful identification of the preferred basis, which is approximately the position basis, demonstrates that the B-particles are unnecessary for defining the preferred basis. They bolster arguments regarding the significance of the wave function and the seriousness with which one should regard its structures. In a discussion of consciousness, they go so far as to state the following:

> To restrict supervenience of consciousness to de Broglie–Bohm corpuscles in the brain does succeed in restricting conscious goings-on to one and only one branch of the Everett multiverse but it seems unwarranted and bizarre.

The are several responses from proponents of dBB. Lewis [18] argues that branches do not necessarily amount to worlds and doubts that "empty wave function branches contain measurement results". This shows that Lewis fails to trust that the wave function structures can represent something similar to what the particles do. Similarly Maudlin [19] states the following:

> All of this talk of a wavepacket 'representing' an outcome is unfortunate: what the wavefunction monist has to defend is that the outcome just is the wave function taking a certain form. . .
>
> . . .The whole of Brown and Wallace's paper appears to be an attempt to simply dodge this point and to assert, without discernible argument, that the structure of the wave function alone is sufficient to account for macroscopic reality.

Maudlin notes that Damour interprets the wave function amplitude as an 'existence amplitude'. However, Maudlin finds no meaning in that term and asks "what such 'intensity of existence' could connote". Maudlin also argues that in theories where the wave function offers a complete ontology, the domain of the wave function cannot be the classical configuration space. His reasoning was that "We are not yet entitled to call this space 'configuration space' since there is no low-dimensional space at all and a fortiori, there is nothing configured one way or another in it". Maudlin's article has the provoking title "Can there be only wave function?"

Valentini [20] defends dBB from his position that dBB does not obey Born's rule, and thus, cannot be the same as a theory that obeys the Born rule. Nevertheless, he brings up cases in which two wave packets move away from each other. The potential energy varies slowly, so the Ehrenfest theorem applies. One of the wave packets pilots B-particles, and the other is empty. Valentini finds that the empty wave packet is "simulating the approximately classical motion". Here, he acknowledges a strong similarity between an empty wave packet and an occupied one. He even goes as far as to write that "if one wishes one may identify the flow with a set of trajectories representing parallel (approximately classical) worlds". However, he then continues:

> But if we start from pilot-wave theory understood on its own terms, there is no motivation for doing so: such a step would amount to a reification of mathematical structure (assigning reality to all the trajectories associated with the velocity field at all points in phase space). If one does so reify, one has constructed a different physical theory, with a different ontology; one may do so if one wishes, but from a pilot-wave perspective there is no special reason to take this step.

Goldstein [21] defends dBB with:

> it seems that one could consider, at least as a logical possibility, a world consisting of particles moving according to some well-defined equations of motion, and in particular according to the equations of Bohmian mechanics. It seems entirely implausible that there should be a logical problem with doing so. We should be extremely skeptical of any argument, like the claim of Deutsch, Brown, and Wallace, that suggests that there is.

Goldstein also argues that Brown and Wallace's arguments are invalid because Vaidman and Wallace view MWI differently.

Let us now evaluate the criticisms of dBB and the responses. Much of early MWI theory has been more visionary than well-defined proposals. Wallace [15,29] has clearly articulated his understanding of MWI. However, his perspective on MWI is lacking, as he does not specify the physical property to which the wave function corresponds. As a result, discussions about structures that can be linked to macroscopic objects, such as cats, become ambiguous. Strictly speaking, it is empty.

Brown and Wallace failed to discuss the dBB theory on its own terms. By doing this, they nearly commit a straw man fallacy. Their assertion that the description of human consciousness is a particularly strong argument for MWI is surprising. It is difficult to understand how consciousness could clarify the question of whether dBB is merely MWI in disguise.

Lewis and Maudlin's responses indicate that they do not recognize how the wave function structures can correspond to physical objects. Maudlin's discussion of Dabour's notion that the wave function is an 'existence amplitude' highlights the significance of defining the physical meaning of the wave function. His concerns about the domain of the wave function, $C(N)$, and his doubts about the wave functions' ability to describe the physical world are unfounded, as demonstrated in Section 2.

Valentini's response is interesting because he somewhat agrees with the criticism of dBB but claims there is no reason to view dBB from a different perspective than the straightforward one. This display of intellectual conservatism cannot be regarded as a valid response. Goldstein's defense is oversimplified when he asks us to concede that dBB is "at least a logical possibility", as the critics' point is that what may initially appear to be a possibility, upon further investigation, turns out not to be so. Like Valentini, Goldstein seems reluctant to openly consider the critics' perspective. The fact that Vaidman and Wallace view MWI differently is not, in itself, an argument against the criticism from Brown and Wallace.

Two clear prerequisites must be met to demonstrate the thesis that "dBB is MWI". First, MWI must be a well-defined theory that both advocates of dBB and others consider to be a principled description of the world, which is the purpose of Section 2. Additionally, any argument should acknowledge how proponents interpret the dBB theory.

A New Argument for dBB Is MWI—The Ghost Argument

The perspective on MWI presented in this article is closely linked to the guiding equation for the B-particles. The ontology comprises a fluid ρ that exists in $C(N)$ and an intricate spin state, χ, connected to it. However, neglecting the spin, MWI is merely all possible dBB trajectories as a collective entity. The explanation of the manifest image and the appearance of classical mechanics equally depend on the decoherence theory in each interpretation. The discussion of dBB in Section 3 demonstrates that dBB, as perceived by its proponents, is a realistic interpretation of quantum mechanics, though it is not as exceptional as they have argued. No unique methods exist within its framework that are unavailable in MWI. This is significant because such methods would suggest that dBB cannot be MWI in disguise.

There is a more compelling way to articulate the criticism against dBB that cannot be dismissed. This argument acknowledges that, according to dBB, the constituents of matter in this world are the B-particles. Viewed in this way, dBB appears entirely logical and consistent. In worlds without B-particles, there is no matter, only a 'force field' lacking anything to act on. Still, a lot is going on in the wave function of those branches. If what occurs there does not involve anything material, we might describe it as ghostly. The realms where nothing material exists will be called ghost branches. To grasp that something is occurring there and what it is, you only need to consider the (time-dependent) flow lines defined by the currents. There are structures of the wave function that correspond to humans doing the things humans do and living in the ghostly environments corresponding to the environments humans live in. There can be structures that correspond to a human calling himself Tim Maudlin, who claims to favor dBB rather than MWI. Of course, according to dBB, these are not people as they are not material. Thus, we can call them ghosts. The problem for proponents of dBB is to find out if they consist of real matter or are ghosts. However, there is no possible observation that can give guidance. Even if dBB is correct, no one can tell if they are ghosts or real, rendering the B-particles irrelevant.

5. Discussion

'The Ghost Argument' is not a clever philosophical maneuver, nor can it be avoided by such a move. It is an adaptation of a general operational rule for scientists. Whenever we have a model or theory, we cannot take for granted that it contains exactly what we intended or what it seemed to contain when we first came to know it. We should always examine all its features with an open mind. Often, one finds that a proposal is more limited than anticipated. When luck strikes, it is much more fruitful. On other occasions, one finds that the theory was completely different than intended.

The term 'hidden variable' expresses that what physicists can investigate is the wave function. Where or when the next detection will come is hidden. Bohm and Bell turned that around and said that what has been thought of as hidden is what we see. The ghost argument is turning that around, saying no, you are not seeing those things you imagined.

The non-local interaction in the dBB theory and the related troubles with respect to relativity are real downsides to the dBB theory. MWI is a local theory. The reason to believe in a violation of relativity boils down to the fact that we get a more pleasant ontology. However, as argued above, this ontology is not particularly attractive and can certainly not outweigh the fact that it forces us to accept the violation of relativity, even if it is very subtle. The Born rule is well explained in MWI by the present author, and many other attempts, too many to review here, give interesting insights into the appearance of probability in MWI. The Born rule in MWI is not primarily about the epistemic kind of probability but something new, as Everett [9] realized. This is a pedagogical problem, not a real scientific problem.

However, 'The Ghost Argument' gives us no choice. The dBB theory is a many-world theory with a B-particle extra ontology with infinitely low relevance. To clarify the situation. If dBB is correct, then B-particles have exactly the same information content as the single flow line they follow. Thus, one could as well have taken the alternative theory, which defines reality as this particular flow line. Here, the dBB proponent might say the point is that dBB is not that, period. But if you are to be open-minded, which one has to be, you have to admit that it would be a very similar theory to dBB. Thus, you could not deny it would work. Then, one has to admit that nearby flow lines are just as good. Then, a whole bunch of nearby flow lines, which is a world in the many-world sense, can also describe reality in an acceptable manner. This granted, MWI also describes reality. Inversely, if MWI fails, no bunch of nearby flow lines corresponds to the world we experience, meaning that there is no single flow line that can explain our world either. If that is the case, the B-particles must also fail. This makes the same point as the ghost argument: a bunch of flowlines is just as plausible as a description of physical reality as that of the B-particles. That the world consists of point particles like the B-particles thus seems utterly implausible.

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