Can the wave function of the universe be a law of nature?

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Abstract

It has been debated whether the wave function of the universe is ontic or nomological in a quantum theory in which the wave function is real, such as Bohm's theory. In this paper, I argue that a natural way to explain the result of a protective measurement is to admit that the wave function is ontic, representing a concrete physical entity. The ontic view of the wave function satisfies the principle of locality for product states, as well as the causal closure principle, while the nomological view of the wave function violates the principle of locality for product states, and it can hardly satisfy the causal closure principle either.

> In any case, the most hidden of all variables, in the pilot wave picture, is the wavefunction, which manifests itself to us only by its influence on the complementary variables. (Bell, 1987)

> no experiment can directly *reveal* the quantum state of any system: our only clues to the quantum state are inferences from the behavior of the Primary Ontology. (Maudlin, 2013)

It has been suggested that the wave function of the universe is not ontic, representing a concrete physical entity, but nomological, like a law of nature (Dürr, Goldstein and Zanghì, 1997; Allori et al, 2008; Goldstein, 2017). On this view, there are only particles in three-dimensional space in Bohm's theory, and mass density distribution in GRWm theory, and flashes in GRWf theory, etc. In this paper, I will argue that when explaining the result of a protective measurement, the nomological view of the wave function violates the principle of locality for product states, and it can hardly satisfy the causal closure principle either, while the ontic view of the wave function can solve these issues in a natural way; it satisfies both the causal closure principle and the principle of locality for product states.[1]

Let's first see a familiar example in classical mechanics. Suppose in an isolated lab there are a particle with charge Q trapped in an uncharged box and a test electron. The test electron is shot along a straight line near the box, and then detected on a screen after passing by the box. According to Newton's laws of motion and Coulomb's law, the deviation of the trajectory of the test electron is determined by the charge of the measured particle, as well as the distance between the electron and the particle. If there were no charged particle in the box, the trajectory of the electron would be a straight line as denoted by position "0" in Figure 1. Now, the trajectory of the electron will be deviated by a definite amount as denoted by position "1" in Figure 1.

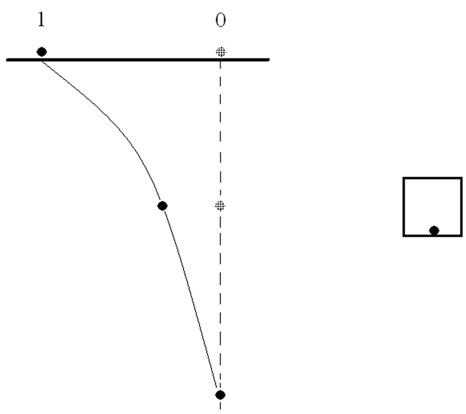

Figure 1: Scheme of a measurement of the charge of a classical particle

The question is: What makes the test particle deviate from its free trajectory? According to the causal closure principle, the deviation of the test electron as a physical effect must be due to a physical cause. Obviously, the cause is that the measured particle has a charge Q in its position in the box, which has the efficacy to deviate the test electron from its free trajectory. If there is no charge in the box, then the deviation of the test

[1]Note that Humeanism about laws already violates the causal closure principle, which says that all physical effects have physical causes, since there are no necessary connections such as causes and effects on this view. I will not discuss this view in this paper. Besides, primitivism about laws is compatible with my conclusion that the wave function represents a physical entity, since it admits the law such as the universal wave function in Bohm's theory as part of the fundamental ontology (Maudlin, 2007). In this sense, primitivism about laws does not belong to the nomological view of the wave function. I will not discuss it either in this paper.

electron as a physical effect, if it still exists, will have no cause. In this case, the causal closure principle will be violated, and the theory will be plagued by an explanatory deficiency problem.

Now let's consider a similar example in quantum mechanics. Suppose in an isolated lab there are a quantum system with charge Q trapped in an uncharged box and a test electron. The quantum system is in the ground state $\psi_1(x)$ in the box. The test electron, whose initial state is a Gaussian wavepacket narrow in both position and momentum, is shot along a straight line near the box. The electron is detected on a screen after passing by the box. Suppose we make an adiabatic-type protective measurement of the charge of the system in the box.[2] Then, according to the Schrödinger equation with an external Coulomb potential, the deviation of the trajectory of the electron wavepacket is determined by the modulus squared of the ground state of the measured system multiplied by the charge of the system, namely $|\psi_1(x)|^2 Q$, as well as the distance between the electron wavepacket and the box. Moreover, the ground state of the measured system does not change during the measurement. If there were no charged quantum system in the box, the trajectory of the electron wavepacket would be a straight line as denoted by position "0" in Figure 2. Now, the trajectory of the electron wavepacket will be deviated by a definite amount as denoted by position "1" in Figure 2.

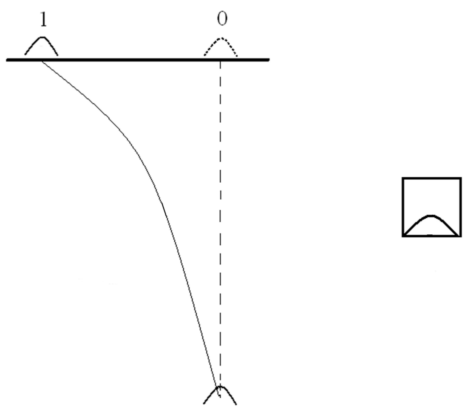

Figure 2: Scheme of a protective measurement of the charge of a quantum system

[2]The conditions for making such an adiabatic-type protective measurement are: (1) the measuring time of the electron is long enough compared to $\hbar/\Delta E$, where ΔE is the smallest of the energy differences between the ground state and other energy eigenstates, and (2) at all times the potential energy of interaction between the electron and the system is small enough compared to ΔE (Aharonov and Vaidman, 1993; Aharonov, Anandan and Vaidman, 1993; Gao, 2015, 2017).

Then, what makes the electron wavepacket deviate from its free trajectory? According to the causal closure principle, the deviation of the electron trajectory as a physical effect must be due to a physical cause. Then, if the wave function is real, representing a realistic property of a quantum system (Pusey, Barrett and Rudolph, 2012), it will be natural to assume that the cause is that the measured system has a physical property $|\psi_1(x)|^2 Q$ in each position x in the box, which by definition has an efficacy to deviate the test electron from its free trajectory. This is similar to the classical situation. We may call this property charge distribution, whose density is $|\psi_1(x)|^2 Q$ in each position x. If the deviation as a physical effect has no cause, then the causal closure principle will be violated, and the theory will be plagued by an explanatory deficiency problem.

This argument can be generalized to an arbitrary wave function. For a quantum system with charge Q whose wave function is $\psi(x)$ at a given instant, we can make a protective measurement of the charge of the system in a small spatial region V having volume v near position x. This means to protectively measure the following observable:

$$A = \begin{cases} Q, & \text{if } x \in V, \\ 0, & \text{if } x \notin V. \end{cases} \tag{1}$$

The result of the measurement is

$$\langle A \rangle = Q \int_V |\psi(x)|^2 dv. \tag{2}$$

By the same reasoning as above, the causal closure principle requires that the measured system has a charge $Q \int_V |\psi(x)|^2 dv$ in region V (when the wave function is real), which has the efficacy to move the pointer of the meter and yield the result of the protective measurement. Then when $v \to 0$ and after performing measurements in sufficiently many regions V, we can find that the measured system has a charge distribution in the whole space, and the charge density in each position x is $|\psi(x)|^2 Q$. Similarly, we can protectively measure another observable $B = \frac{\hbar}{2mi}(A\nabla + \nabla A)$. The causal closure principle requires that the measured system also has an electric flux distribution in space, and the electric flux density in each position x is $j_Q(x) = \frac{\hbar Q}{2mi}[\psi(x)^* \nabla \psi(x) - \psi(x) \nabla \psi(x)^*]$.[3]

Since these two real densities can constitute the complex wave function, this also means that the wave function of the measured system $\psi(x)$ represents the state of a physical entity which exists in the whole space where the wave function is nonzero (during an arbitrarily short time interval when the protective measurement can be made). Moreover, if the measured system has charge Q, the physical entity will have a charge density $|\psi(x)|^2 Q$ in each position x in space, as well as an electric flux density as given above.

[3]These results can also be generalized to a many-body system (see Gao, 2017).

Now an intriguing question arises: Must the cause of the moving of the pointer or the physical property $|\psi(x)|^2Q$ be a property of a physical entity existing in position x? It seems that the answer may be negative. It is in principle possible that an empty space can also deviate the nearby test electron from its free trajectory, if only there is a physical entity existing elsewhere, and it can excert a nonlocal influence on the test electron, which is determined by its physical property $|\psi(x)|^2Q$. Let's consider this possibility more carefully.

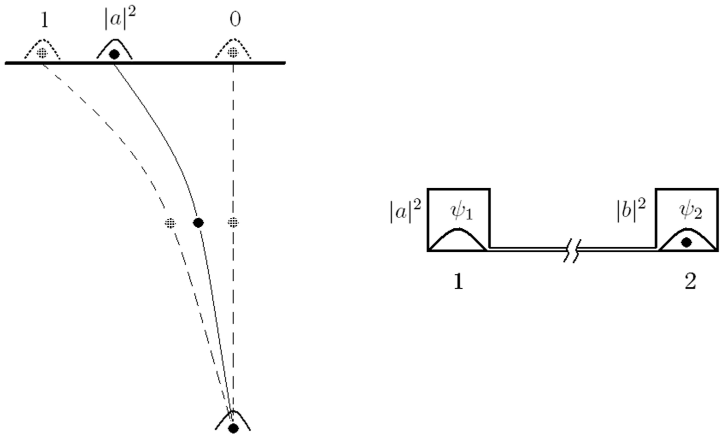

Figure 3: Scheme of a protective measurement of the charge of a quantum system in Bohm's theory

Take Bohm's theory as a typical example. For the sake of simplicity, suppose in a universe there are only a measured system with charge Q, trapped in a two-box protective potential, a test electron and a detecting screen (see Figure 3). The wave function of the measured system at the initial instant is $\psi(x) = a\psi_1(x) + b\psi_2(x)$, where $\psi_1(x)$ and $\psi_2(x)$ are two normalized wave functions respectively localized in their ground states in two small identical boxes 1 and 2, and $|a|^2 + |b|^2 = 1$. A test electron, whose initial state is a Gaussian wavepacket narrow in both position and momentum, is shot along a straight line near box 1 and perpendicular to the line of separation between the two boxes. The electron is detected on a screen after passing by box 1. Suppose the separation between the two boxes is large enough so that a charge Q in box 2 has no observable influence on the electron. Then if the system is in box 2, namely $|a|^2 = 0$, the trajectory of the electron wavepacket will be a straight line as denoted by position "0" on the screen. If the system is in box 1, namely $|a|^2 = 1$, the trajectory of the electron wavepacket will be deviated by a maximum amount as denoted by position "1" on the screen. When we make a protective measurement of the charge of the system in box 1 for the superposition $\psi(x)$, the trajectory of the electron wavepacket is determined by the expectation value of the charge of the system in box 1, and thus it will be deviated by an intermediate amount as denoted by position "$|a|^2$" between "0" and "1" on the screen.

According to the nomological interpretation of Bohm's theory, the wave function of this universe being a product state is nomological, and there are only a measured particle and a test particle (besides the box and screen particles) in the universe. Moreover, during the protective measurement, the measured particle has been at rest in a position in the boxes, since the measured system stays in the same energy eigenstate throughout the process. Then, by the same reasoning as before, the causal closure principle requires that the measured particle has a physical property represented by $|a|^2Q$ (namely the modulus squared of the wave function of the measured system in box 1 multiplied by the charge of the system), which by definition enables it excert a nonlocal influence on the test electron to deviate it from its free trajectory. The nonlocality of the influence is more obvious when the measured particle is in box 2, being far away from the test particle. The question is: Does this kind of nonlocal influence exist in Bohm's theory? If it does not exist, then the theory will violate the causal closure principle.

Let's see the main non-Humean view of laws, dispositionalism (Esfeld et al, 2014). On this view, there are only particles which have both positions and disposition, and the universal wave function represents a holistic disposition of all particles in the universe which determines their motion. In the above example, since the universal wave function is a product state, the holistic disposition is separable, and the measured particle and the test particle have their respective dispositions represented by their wave functions. In particular, the wave function of the measured system represents the disposition of the measured particle that determines only its own motion, letting it be at rest in a position in the two boxes, and the disposition is realized only in this position and not in all other positons including box 1. Moreover, the measured particle has no properties other than position and this disposition. Thus, according to the Bohmian dispositionalism, the measured particle has no influences, either local or nonlocal, on the test particle, and the deviation of the trajectory of the test particle has no cause. This means that this view violates the causal closure principle.

There is a deeper reason why the Bohmian dispositionalism fails to explain the deviation of the trajectory of the test particle during a protective measurement. It is that this view does not consider the usual interactions between quantum systems. Entanglement is indeed important to explain some strange quantum phenomena, but it certainly cannot explain all interactions between quantum systems. The interaction between the measured system and the measuring system during a protective measurement is irrelevant to entanglement, since the wave function of the composite system has been a product state throughout the measurement. Moreover, it is obvious that the interactions between objects in the emergent classical world are not relevant to entanglement in general. Such interactions include EM and gravitational interactions, and they are represented by the potential terms in the Schrödinger equation. In the above example of protective measurement, the interaction between the measured system and the measuring system is part of the EM interactions, the electrostatic interaction. The motion of the test particle also depends on the value of Q of the measured system besides its wave function, e.g. when $Q = 0$ the motion of the test particle is not deviated from its free trajectory.

Even if we consider entanglement such as the universal wave function being an entangled state, the EM and gravitational interactions are also important since they determine the evolution of the entangled state over time. In fact, if there were no such interactions, the entangled state could not even be formed in the first place. It seems that the Bohmian dispositionalism only emphasizes the entangled nature of the universal wave function being a holistic disposition of all particles in the universe, but ignores the usual interactions that form the entangled universal wave function and further determine its evolution over time. It is the ignorance of usual interactions that makes this view fail to explain the deviation of the trajectory of the test particle in the above example and thus violate the causal closure principle.

Can the Bohmian dispositionalism avoid the violation of the causal closure principle by adding the nonlocal influences? The answer seems negative. First of all, the existence of such nonlocal influences violates the principle of locality for product states, which says that the interactions between two systems being in a product state are local. In fact, all realist quantum theories in which the wave function does not represent a physical entity will violate the principle of locality for product states. On the other hand, the principle of locality for product states requires that the wave function represents a physical entity (when it is real). According to this principle, since the interaction between the measured system and the meter in position x is determined by $|\psi(x)|^2 Q$ during the above protective measurement, this quantity must represent a property of a physical entity existing in position x (during the measuring period which may be arbitrarily short). If otherwise there exists only a physical entity being in another position, then the interaction between the entity and the meter will be nonlocal, violating the principle of locality for product states. Although there exists nonlocality for entangled states in quantum mechanics, and the above violation of locality for product states is not inconsistent with experience, it is still in want of a reasonable explanation.

Next, even if the violation of locality for product states is permitted and the required nonlocal influences may exist, the origin of the nonlocal influences can hardly be explained, and the theory will also have various unnatural features. Let me restate why the measured particle must have a physical property which enables it excert a nonlocal influence on the test electron in the above example. According to the Bohmian laws of motion, the motion of the test particle is determined by both the wave function of the measured system in box 1 and the charge of the measured system. Concretely speaking, it is determined by the term $|a|^2 Q$. Thus, the cause of the deviation of the trajectory of the test particle should be a physical property described by this mathematical term (when the wave function is real). Since the ontology of the Bohmian dispositionalism consists only in particles, this property must be a property of the measured particle being at rest in a position in box 2 (see Figure 3). This means that the measured particle must have a physical property described by $|a|^2 Q$, maybe called charge, which enables it exert a nonlocal influence on the test particle.

However, endowing the measured particle in box 2 (not another physical entity in box 1) with such a charge property seems very unnatural. The reason is as follows. First, the charge endowed to the measured particle cannot be shielded. When using a Faraday shield for box 2, the influence on the test particle still exists and does not change. But when using a Faraday shield for box 1, the influence on the test particle no longer exists. Next, since there is only the measured particle which influences the test particle, if the degree of the influence depends on a distance, then it seems that the distance must be the distance between the measured particle and the test particle. There is only a distance relation between them after all; there are no other particles interacting with the test particle, and in particular, there is no particle or another physical entity existing in box 1. But the degree of the influence is determined not by the distance between the test particle and the measured particle, but by the distance between the test particle and box 1 where the modulus squared of the wave function of the measured system is $|a|^2$. Third, the influence is always a repulsion relative to box 1 and its direction is always along the line extending from box 1. But it may be a repulsion or an attraction relative to the measured particle in box 2, depending on the initial position of the test particle; if the initial position of the test particle is between the two boxes, then the influence will be an attraction relative to the measured particle. Morover, the direction of the influence is independent of the measured particle in box 2. Fourth, although the assumed influence exerted by the measured particle is nonlocal, it has a time delay determined by the distance between the test particle and box 1 in the relativistic domain, where the EM interactions are mediated by fields propagating with the speed of light.

In fact, all features of the influence relate to box 1 and not to the measured particle in box 2. No matter where box 2 and the measured particle are, how they move, whether the measured particle annihilates with another anti-particle, and what form the wave function of the measured system in box 2 is, and so on, if only box 1 keeps unchanged, the influence will keep unchanged. On the other hand, even if there is no any change in the region of box 2 and the measured particle, if only there is a change in box 1, such as the size of the box being enlarged very slowly, which may influence the wave function of the measured system in box 1, then the influence will change.

Finally, all these strange features can be explained in a natural way when assuming that the physical property described by $|a|^2 Q$ is not a charge property of the measured particle, but a charge property of another physical entity which exists in box 1 where the modulus squared of the wave function of the measured system is $|a|^2$. Similarly, there is also a physical entity existing in box 2 where the modulus squared of the wave function of the measured system is $|b|^2$. This reaffirms my previous conclusion that the wave function of the measured system $\psi(x)$ represents a physical entity extending in space, including both boxs 1 and 2, where the wave function is nonzero. Certainly, what the physical entity really is poses another deeper issue (see Gao, 2017; Hubert and Romano, 2018 for a recent analysis). I will analyze this issue in future work.

To sum up, I have argued that in a quantum theory in which the wave function is real, such as Bohm's theory, a natural way to explain the result of a protective measurement is to admit that the wave function is ontic, representing a concrete physical entity. The ontic view of the wave function satisfies both the causal closure principle and the principle of locality for product states. While the nomological view of the wave function, such as the Bohmian dispositionalism, violates the principle of locality for product states, as well as the causal closure principle. Although adding nonlocal influences between systems being in a product state may avoid the violation of the causal closure principle, the origin of these influences can hardly be explained, and the revised theory also has various unnatural features.

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