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# DID BOHR SUCCEED IN DEFENDING THE COMPLETENESS OF QUANTUM MECHANICS?

KUNIHISA MORITA
*Okasa University,* JAPAN
`kunihisa@e-mail.jp`

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**Abstract.** This study posits that Bohr failed to defend the completeness of the quantum mechanical description of physical reality against Einstein–Podolsky–Rosen's (EPR) paper. Although there are many papers in the literature that focus on Bohr's argument in his reply to the EPR paper, the purpose of the current paper is not to clarify Bohr's argument. Instead, I contend that regardless of which interpretation of Bohr's argument is correct, his defense of the quantum mechanical description of physical reality remained incomplete. For example, a recent trend in studies of Bohr's work is to suggest he considered the wave-function description to be epistemic. However, such an interpretation cannot be used to defend the completeness of the quantum mechanical description.

**Keywords:** Bohr • EPR experiment • completeness of quantum mechanics • epistemic view of wave-function • description of physical reality

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## 1. Introduction

In this paper, I show that Bohr (1935) failed to defend the completeness of the quantum mechanical description of *physical reality* against Einstein–Podolsky–Rosen's (EPR) paper (Einstein et al. 1935), which asserts that the quantum mechanical description of physical reality is incomplete. There are many studies in the literature that seek to clarify Bohr's argument in his reply to the EPR paper (Beller and Fine 1994; Howard 1994, 2004; Halvorson and Clifton 2001), but that is not the focus of the current paper.

In general terms, there are two points to consider as regards Bohr's argument. The first is whether Bohr considered the wave-function to completely describe (Ia) the *physical* state of the system in question or (Ib) the state of *our knowledge* about the system, and the second point is whether (IIa) or not (IIb) he accepted the concept of the collapse of the wave-function. There are four combinations of these options that must be considered; although, as discussed below, Bohr's position did not consist of a combination of (Ia) and (IIa). Therefore, the objective of this paper is to demonstrate that the remaining three combinations are not sufficient to defend the completeness of the quantum mechanical description of physical reality.

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It is not clear from his writings whether Bohr accepted the collapse of the wave-function. Even though Bohr never referred to the collapse of the wave-function (Halvorson and Clifton 2001; Howard 2004; Faye 2008), this does not guarantee that Bohr rejected the collapse. In addition, according to Zinkernagel (2016, p.12), Bohr actually referred to the collapse of the wave-function in his unpublished draft of the Como lecture in 1927. However, the fact that this reference is in an unpublished draft but does not appear in the published paper of the lecture, and the fact that he never referred to the collapse afterward seem to reinforce the claim that he did not accept the concept of the collapse in 1935 when he replied to the EPR paper.

Nevertheless, a significant reason why I consider Bohr to have rejected combination (Ia) and (IIa) is that he clearly denies "mechanical disturbance of the system [. . . ] during the last critical stage of the measuring procedure" (Bohr 1935, p.700). In other words, if the collapse of the wave-function that describes the physical state of the system is accepted, then it is also necessary to accept the existence of a mechanical disturbance of the system because the wave-function that describes the state of the second particle collapses at the same time that the wave-function that describes the state of the first particle collapses in the EPR situation.[1] Therefore, Bohr must not have accepted the combination of (Ia) and (IIa).

A second reason why I consider Bohr to not have accepted this is that as Halvorson and Clifton (HC) also pointed out (2001, p.5), acceptance of the collapse and that the wave-functional description is physical follows acceptance of incompleteness (although HC perhaps consider that acceptance of the collapse immediately follows the acceptance of incompleteness, which is different from my assertion that the combination of (Ia) and (IIa) results in incompleteness). Although HC does not clearly explain their reasoning, I provide my understanding of that reasoning here as follows. The process of collapse cannot be described by the Schrödinger equation; however, if the process is physical and quantum mechanics provides us with a complete description of physical reality, the Schrödinger equation should be able to describe the collapse process.[2] Thus, if the combination of (Ia) and (IIb) is accepted, it means the quantum mechanical description is incomplete. On the other hand, the completeness can be maintained if it is accepted that the collapse process is not the physical process (Brown 1985, p.151), because the question under consideration is whether or not quantum mechanics can completely describe *physical* reality. Nevertheless, there is no clear evidence that Bohr believed that physical processes could be affected by processes other than physical processes. The fact that Bohr did not refer to the possibility of extra-physical phenomena, does not imply that he rejected them. However, it is implausible that Bohr did not refer to this in his response to the EPR paper if he had considered this concept.

The combination of (Ia) and (IIa) is the core of the so-called "Copenhagen interpretation", or standard interpretation,[3] and recent works (Howard 1994; Gomatam

2006; Camilleri 2009) show that Bohr's interpretation and the Copenhagen interpretation differ, and are actually incompatible.

It should be noted that Bohr's usage of the term "classical" is extremely vague. However, HC (2001) and Howard (1994) insist that Bohr's concept of classical (state) refers to the appropriate mixture state. Indeed, a notable feature of quantum mechanics is existence of the interference term. Thus, it is plausible that the classical state equals the appropriate mixture state in modern terminology. Of course, there is also the possibility that their interpretation of classical is incorrect. Nevertheless, as far as I am aware, the EPR problem can only be solved by adopting this definition of classical.

The remainder of this paper is organized as follows. In Section 2, contextual realism is introduced to avoid the conclusion of the EPR paper, which was the approach adopted by Bohr according to HC (2001). In Section 3, the combination of (Ia) and (IIb) is examined, and in Section 4, combinations (Ib) and (IIa), and (Ib) and (IIb) are explored. Finally, conclusions and discussion are provided in Section 5.

## 2. HC's interpretation of Bohr's reply

The EPR paper defines the completeness of theory as follows:

> Whatever the meaning assigned to the term *complete*, the following requirement for a complete theory seems to be a necessary one: *every element of the physical reality must have a counterpart in the physical theory*. (p.777: italic is original)

This definition is natural and intuitive, and it is worthwhile to note that Bohr did not contradict this definition in his reply to the EPR paper. The EPR paper goes on to describe the sufficient condition of reality as follows:

> *If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity*. (p.777, the italics are in the original)

Bohr asserts that the phrase "without in any way disturbing" is ambiguous (1935, p.700). However, as discussed in Section 1, Bohr rejects action-at-distance (mechanical non-locality). Therefore, many authors (Howard 1994; 2004; Halvorson and Clifton 2001; Zinkernagel 2016) consider Bohr to have introduced so-called "contextual-dependent realism", which means that the set-up of the experiment influences which physical quantities are real. Thus, in a sense, the system is disturbed by the set-up of the experiment. HC (2001) in particular thoroughly developed this concept.

In what follows, I focus on HC's work because it is sufficient for the purposes of this work.

In their work, HC (2001) state the following:

> [...] a measurement on the first system influences the conditions that must be obtained in order for us to "define" the elements of reality for the second system. Moreover, this influence is of such a sort that a position (momentum) measurement on the first particle supplies the conditions needed to define the position (momentum) of the second particle. (pp.4–5).

According to HC (and Howard 1994), Bohr's notion of a "classical description" in fact indicates an "appropriate mixture". Furthermore, HC claimed the following in their work:

> An appropriate mixture is supposed to give a description in which the measured observable is an "element of reality". (p.7)
>
> [...] the theorist is not free to make a willy-nilly choice of which elements of reality to ascribe to the second particle; rather, her choice is to be fixed (in some, yet to be explicated, way) by the measurement context. (p.10)

A measurement context can be represented by the pair $(\Psi, R)$, where $\Psi$ is a unit vector representing the quantum state and $R$ is a self-adjoint operator representing the measured observable. To illustrate, consider a spin version of the EPR experiment suggested by Bohm (1951, pp.614f). An ensemble of spin-1/2 particles in the singlet state can be prepared as follows:

(1) $$\Psi = (|x+\rangle|x-\rangle - |x-\rangle|x+\rangle)/\sqrt{2}$$

where $\sigma_x|x\pm\rangle = \pm|x\pm\rangle$. When the $x$-spin of the first particle is measured in the spin version of the EPR experiment, $(\Psi, \sigma_x \otimes I)$ represents the measurement context of the first particle. In this case, according to HC's interpretation, Bohr insisted that the correct description of the present measurement context is $S_{xx}$, which can be defined as follows:

(2) $$S_{xx} = \{P^{x_+} \otimes P^{x_-}, P^{x_-} \otimes P^{x_+}\}$$

where $P^{x_\pm}$ denotes a projection onto the ray generated by $|x_\pm\rangle$ (Halvorson and Clifton 2001, pp.8–10). HC proceeded to show why Bohr believed this description to be correct.

In summary, the statement that the setting of the experiment determines the appropriate mixture state appears to support Bohr's reply to the EPR paper if he tries to avoid the EPR argument by introducing contextual-dependent realism. The following is from the EPR paper:

> One could object to this conclusion on the grounds that our criterion of reality is not sufficiently restrictive. Indeed, one would not arrive at our conclusion if one insisted that two or more physical quantities can be regarded as simultaneous elements of reality *only when they can be simultaneously measured or predicted*. On this point of view, since either one or the other, but not both simultaneously, of the quantities $P$ and $Q$ can be predicted, they are not simultaneously real. This makes the reality of $P$ and $Q$ depend upon the process of measurement carried out on the first system, which does not disturb the second system in any way. (1935, p.780)

Therefore, the authors of the EPR paper themselves admit that contextual-dependent realism can resolve the paradox, although they reject this solution because "[n]o reasonable definition of reality could be expected to permit this".

However, the question under consideration is as follows. Does contextual-dependent realism (which means that the wave-functional description is epistemic) actually allow the completeness of the quantum mechanical description to be defended? In the next section, it is shown that the combination of (Ia) and (IIb) is not sufficient to defend the completeness of the quantum mechanical description, and in fact it may be more accurate to say that (Ia) and (IIb) are incompatible. In short, if a wave-function completely describes a physical system, it must collapse when the physical quantity in the system has one definite value.

## 3. Can a quantum mechanical description of physical reality be considered complete?

Although Bohr succeeded in defending the uncertainty relationship that makes it impossible to simultaneously predict values of both position and momentum, by introducing contextual realism, it can be shown that he ultimately failed to defend the completeness of the quantum mechanical description of physical reality.

The key point is that even if we accept that the context of a measurement determines a unique appropriate mixture state, this still does not explain why the value of a physical quantity can be predicted with certainty. In the EPR experiment (according to HC), Bohr insisted that if we prepare to measure the $x$-axis of a spin (the $x$-spin), a mixture state for the $x$-spin of a second particle in a system is already an element of reality before the measurement of the first particle takes place. However, a mixture state for the $x$-spin of the second particle does not tell us which value ($+1/2$ or $-1/2$) the $x$-spin of the second particle has because a mixture state is not an eigenstate, despite the fact that the $x$-spin of the second particle could have had only one definite value before the first particle was measured. We know this because we can predict the value with certainty and without any mechanical disturbance.

HC might respond to this claim by insisting that Bohr did not believe in the existence of an eigenstate-eigenvalue link, which indicates that a quantity *Q* is defined to be in state Ψ if and only if Ψ is an eigenvector of *Q* (Halvorson and Clifton 2001, p.5). Thus, there is a case in which *Q* has a definite value even when its state is not an eigenstate.

Nevertheless, if we accept this interpretation, then we must also accept the fact that Bohr admits that quantum mechanics is incomplete, as his rejection of the eigenstate-eigenvalue link implies that a wave-function cannot describe a physical state of a quantum system completely. This is because if a wave-function completely describes the reality of a physical quantity *Q*, it must be possible to discover the value of *Q* from the information contained in the wave-function whenever *Q* has a definite value. However, if the eigenstate-eigenvalue link does not hold, we cannot know which value *Q* possesses from the information contained in the wave-function alone, even when *Q* has a definite value. This line of argument will be reconsidered later in this paper.

A possible objection to this conclusion is that Bohr did not state that the second particle has a definite value *before* the first particle is measured. This is actually a plausible supposition; however, even if the above assumption is correct, Bohr was still unable to defend the completeness of quantum mechanics. We can predict the value of the second particle *after* the measurement of the first particle has taken place. Thus, the second particle must, at a minimum, have a definite value *after* the measurement of the first particle has already occurred. Note that consideration of a case in which the many-worlds interpretation is correct is beyond the scope of this paper because only Bohr's argument is under consideration.

Presently there are two options concerning the state of the second particle *after* the first particle is measured: (A) it changes into an eigenstate, or (B) it does not change. Option (A) implies that the wave-function has collapsed. However, accepting that the wave-function has collapsed leads to acceptance of the incompleteness of quantum mechanics, as discussed in Section 1. Option (B) implies that the eigenstate-eigenvalue link does not hold and, as discussed above, this also indicates that quantum mechanics is incomplete.

Therefore, while EPR explicitly declare that they do not accept contextual-dependent realism (Einstein et al., 1935, p.780), even if they did accept such a reality, the argument for the incompleteness of quantum mechanics based on the EPR experiment is still valid.

## 4. Does the wave-function describe the physical system?

At this point, the findings of the present study can be summarized as follows:

(1) We can predict a physical quantity (e.g., the $x$-spin) of the second particle in a system with certainty and without causing any *mechanical* disturbances by measuring the $x$-spin of the first particle.

(2) Point (1) implies that the $x$-spin of the second particle possessed a definite value before the first particle was measured, based on EPR's definition of reality.

(3) Despite (2), quantum mechanics does not tell us which $x$-spin value the second particle possessed before the first particle was measured (after the interaction), even if the context of the measurement provides a unique appropriate mixture state.

(4) Therefore, the quantum mechanical description of physical reality is incomplete based on EPR's definition of completeness.

Another possible objection to this line of reasoning is that Bohr highlighted the ambiguity in the phrase "without in any way disturbing a system" in the EPR paper (Einstein et al., 1935, p.777). However, Bohr's intention was to emphasize that EPR did not consider the measurement context, which was that the measurement of the first particle influences the *condition* under which an element is part of reality, and that he accepted the absence of *mechanical* disturbances in EPR situations, which is unlike the proponents of the Copenhagen interpretation. This raises the question, are there any persuasive conditions of reality that can reject the reality in spite of the fact that we can predict a physical quantity with certainty and without any mechanical disturbances?

Nevertheless, it is possible to object by insisting that Bohr considered other conditions of completeness. In the previous sections, it was claimed that rejection of the eigenstate-eigenvalue link indicated acceptance of the incompleteness of the quantum mechanics according to the condition of completeness provided in the EPR paper, but this conclusion is only valid in the case where Bohr's position is (Ia), which is that the wave-function describes the *physical* state of the system. However, if Bohr considered the wave-function to describe the state of our knowledge of a system, then the above conclusion can be avoided, in which case Bohr's position was either a combination of (Ib) and (IIa) or (Ib) and (IIb).

If the wave-function describes our state of knowledge, then the logical transition from (3) to (4) becomes invalid, and the rejection of the collapse of wave-function does not necessarily imply acceptance of the incompleteness of quantum mechanics.

Consider the following example:

Suppose there is a computer program that can produce a completely random series of binary values. Suppose that the probability that either "0" or "1" appears next in the series is exactly 0.5, and thus the average probability of all the values in the entire series occurring is 0.5. We instruct the program to produce a series with 1000 elements from left to right on a piece of paper without observing the process.

Then, we read the values on the paper from left to right after the program has finished printing them out. Although we know that the probability of "1" appearing in the next element is 0.5 at any point in the series, and this is all the information related to the unseen values on the paper that we can obtain, we cannot know which value, "0" or "1", appears next on the paper before we read it. This, of course, does not imply either that values written on the right side of the paper do not yet exist or that they are malleable before we read them. The program has already printed those values, and thus we tend to insist that they already exist and will not change.

A similar process may occur in the quantum world. Once the context of a particle has been determined, the value of its spin has also been determined. However, because the wave-function describes only the state of our knowledge, and we do not know which value the spin has, the fact that the wave-function is not an eigenfunction in spite of the fact that the system is an eigenstate in which a physical quantity has one definite value does not alone indicate that the description of quantum mechanics is incomplete. In addition, although the state of our knowledge of the second particle changes when we measure the first particle in an EPR system, it is not necessary to introduce *mechanical* non-locality. However, even if we take this position, it appears we need to accept the collapse of the wave-function, because when we know the result of the measurement, the state of our knowledge must collapse. Therefore, the combination of (Ib) and (IIb) is impossible. Consequently, only one option remains, the combination of (Ib) and (IIa).

However, can the combination of (Ib) and (IIa) defend the completeness of the quantum mechanical description of *physical* reality? Bohr, according to HC, insists that which physical quantity has a definite value (thus has reality) depends on the context. For example, in the EPR situation, the $x$-spin of the second particle has a definite value in the context of measurement of the $x$-spin of the first particle. However, because the wave-function describes the state of our knowledge, we cannot make predictions prior to the measurement of the first particle. However, accepting that the context determines which physical quantity has a definite value means that no physical quantity has a definite value before determining the context. In other words, immediately after determining the context, such as measuring $x$-spin, the $x$-spin of the second particle has a definite value. Nevertheless, change from the state having no definite value into one having a definite value is clearly physical change. Furthermore, if determination of the context brings about this physical change, there is physical non-locality that Bohr rejects. Therefore, the combination of (Ib) and (IIa) also cannot defend the completeness of quantum mechanical description of the physical reality.[4]

Another issue exists pertaining to the epistemic interpretation; knowledge is time-asymmetric while the Schrödinger equation is time-symmetric. For example, one can measure the $z$-spin at $t_1$ and get a value $+1/2$, and then measure the $x$-spin at $t_2$ ($t_1 <$

$t_2$). It is evident that the individual still has the knowledge that the value of the $z$-spin between $t_1$ and $t_2$ is $+1/2$ even after $t_2$. However, this knowledge cannot retrodict from the wave-function after $t_2$ by the Schrödinger equation. The wave-function after $t_2$ is not the eigenfunction for the $z$-spin because the $x$-spin and $z$-spin are non-commutative. Therefore, if one uses the wave-function after $t_2$ as an initial condition and calculates the wave-function between $t_1$ and $t_2$ using the Schrödinger equation, the result is that the wave-function between $t_1$ and $t_2$ is *not* the eigenfunction for the $z$-spin. This result contradicts the fact that one is aware of the definite value of the $z$-spin as $+1/2$, between $t_1$ and $t_2$. Accordingly, the Schrödinger equation alone cannot explain this asymmetric character of knowledge, and thus, other principles, such as projection postulate, are required for the completeness of quantum mechanics.

Consequently, this solution to the problem of the completeness of quantum theory does not hold.

## 5. Conclusions and discussion

In this paper, I asserted that Bohr did not succeed in defending the completeness of quantum mechanics against the challenge of EPR. According to my analysis, Bohr must have held one of the following four positions.

(1) The wave-function describes a physical state and there is a collapse of the wave-function,

(2) the wave-function describes a physical state and there is no collapse,

(3) the wave-function describes the state of our knowledge and there is no collapse, or

(4) the wave-function describes the state of our knowledge and there is collapse.

However, none of these is sufficient to defend the completeness of quantum mechanics in the natural sense of the completeness of theory.

(1) In this case, there must be mechanical non-locality because the wave-function describing the second particle collapses at the same time as the wave-function describing the first particle collapses by measurement. However, Bohr clearly denied mechanical non-locality.

(2) If the wave-function completely describes the physical state of the system and the physical quantity $Q$ has one definite value, the corresponding wave-function must be the eigenfunction of $Q$. This means that there is a collapse of the wave-function at the moment of measurement because the wave-function is not the eigenfunction until just before the measurement. Thus, the fact that the wave-function describes the physical state and there is no collapse means that the

description of quantum mechanics is incomplete (or, $Q$ does not have one definite value even after the measurement).

In (2), completeness means that the wave-function completely describes the physical state of the system in question (the eigenstate-eigenvalue link works). In (1), the wave-function completely describes the physical state, but the Schrödinger equation, which is the basic equation of quantum mechanics, cannot completely describe the time-development of the wave-function. In both cases, the description of quantum mechanics is incomplete in the natural sense of the completeness of theory. However, if the wave-function is epistemic, the fact that the eigenstate-eigenvalue link does not work does not necessarily mean that quantum mechanics is incomplete. In fact, recent works imply that Bohr appeared to consider the description of wave-function to be epistemic. Nevertheless, this solution does not work.

(3) If the wave-function describes the state of our knowledge of the physical state, collapse must occur at the instant we definitely know the value. However, this is not the case.

(4) In this case, accepting that the context determines which physical quantity has a definite value means that no physical quantity has a definite value before determining the context. In other words, immediately after determining the context, such as measuring $x$-spin of the first particle in the EPR experiment, the $x$-spin of the second particle has a definite value. Nevertheless, change from the state having no definite value into one having a definite value is clearly physical change. Furthermore, if determination of the context brings about this physical change, there is physical non-locality that Bohr rejects.

Some readers might insist that Bohr suggested that the wave-function be regarded symbolically; thus, he did not consider the wave-function as possessing a representational role. Conversely, it simply provides physicists with a probability measure (tool) to observe a particular value. This might be correct. However, if this is the case, then Bohr did not directly answer the criticism by EPR. EPR's concern lies in the completeness of a quantum mechanical description of *physical reality*. Bohr stated the following, after his discussions with Einstein at the Solvay conference in 1927, on Einstein's thought experiment (Bacciagaluppi and Valentini 2009, pp.440ff.):

> I do not know what quantum mechanics is. I think we are dealing with some mathematical methods which are adequate for description of our experiments. (Bacciagaluppi and Valentini 2009, p.442)

The difference between Bohr's view and EPR's view concerning the EPR argument might be based on their differences with respect to the aims of physics. Bohr considered it adequate for physics to save phenomena while Einstein, Podolsky, and Rosen sought physical reality under a mathematical description. Nevertheless, this means that Bohr accepted that quantum mechanics could not offer a complete description of physical reality (although it offers a complete tool to describe the observational data). Hence, it is concluded that Bohr did not succeed in defending the completeness of the quantum mechanical description of physical reality against EPR. He simply changed the rules of the game.

However, researchers might insist that EPR were asking for the moon because of the absence of a complete description of physical reality in principle. There is a possibility that this view is accurate. Nevertheless, there is no proof that it is not possible to offer a complete description of physical reality with respect to a microscopic world. Conversely, I consider that the EPR argument showed us the possibility of a complete description of physical reality in a microscopic world (because we can predict the value of physical quantity with certainty without any mechanical disturbances), and Bohr was unable to deny the aforementioned possibility (i.e., at the very least, he did not show that quantum mechanics completely described physical reality).

Finally, some readers might suggest that the quantum field theory can defend the quantum description of physical reality. However, because the focus of this paper is on the debate between Bohr and Einstein, that issue is, though interesting, beyond the scope of this paper. Therefore, concerning the quantum field theory, I simply refer to Higashi (2009). Heywood and Redhead (1983) demonstrated the impossibility of local truth-value assignment in contextual approach. This work is restricted to the non-relativistic quantum theory. Subsequently, Higashi (2009) also demonstrated the impossibility of local truth-value assignment in a contextual approach even in the case of quantum field theory. This means that quantum field theory cannot avoid the non-locality even when one takes a contextual approach. However, of course, non-locality does not straightforwardly conclude the incompleteness of the quantum mechanical description of physical reality. In future work, I will seek to clarify what exactly Higashi's work means in the context of our current issue.

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## Notes

[1] The experimental fact that the Bell inequality is broken does not necessarily indicate that mechanical non-locality exists and that quantum mechanics is complete (Kupcznski 2017).

[2] Decoherence does not explain the collapse. It only shows that interaction between environment and system eliminates the interference term (but not perfectly) (see Bacciagaluppi 2012). In addition, Myrvold (2016, Section 2.3.3) points out that "if state vector collapse is

to be regarded as a physical process, this raises the question of what *physically* distinguishes interventions that are to count as ‘measurements’, capable of inducing an abrupt jump in the state of the system, from other interventions, which induce only continuous, unitary evolution”.

[3] According to Howard (2004, p.670), “Central to the popular image of the Copenhagen interpretation is the idea that observation-induced wave packet collapse is a mode of dynamical evolution unique to measurement interactions”. As Howard (2004) points out, the term “Copenhagen interpretation” was coined by Heisenberg in 1955 (Heisenberg 1955, p.12).

[4] Here, there is a difference between HC’s version of Bohr’s interpretation and QBism that has recently attracted many physicists (Fuchs 2010; von Baeyer 2016). Although QBism is also an epistemic interpretation, it does not mention reality beyond our experience. Therefore, QBism does not have difficulty, as mentioned in this paragraph.

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