Does the ψ-epistemic view really solve the measurement problem?

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Abstract

It is widely thought that the ψ-epistemic view provides a straightforward resolution or even a dissolution of the measurement problem. In this paper we argue that this is not true. In order to explain the collapse of the wave function merely as a process of updating information about the underlying physical state, this view requires that all observables defined for a quantum system have pre-existing values at all times, which are their eigenvalues. But this requirement contradicts the Kochen-Specker theorem. We also point out that the ontological model framework, on which the existing ψ-epistemic models are based, needs to be extended to solve the measurement problem.

In standard quantum mechanics, it is postulated that if a projective measurement is made on a physical system, its wave function will no longer undergo the normal Schrödinger evolution, but instantaneously and discontinuously collapse to the wave function corresponding to the measurement result. It has been a hot topic of debate how to explain or explain away the collapse of the wave function. The solution to this measurement problem is dependent on the meaning of the wave function. If the wave function does not directly represent a state of reality but merely represent a state of incomplete knowledge about reality, namely if the wave function is not ontic but epistemic, then it seems that the collapse of the wave function can be readily explained as the effect of acquiring new information, no more mysterious than the updating of a classical probability distribution when new data is obtained. For example, in Schrödinger's cat thought experiment, the cat may be definitely dead or alive before we observe it, and the superposition of dead and alive cats we assign to it may simply reflect the fact that we do not know the actual state of the cat. Then after we observe the cat and know whether it is dead or alive, the superposition will naturally be updated by the state corresponding to the dead or alive cat.

There is evidence that Einstein once supported this explanation of the collapse of the wave function. In a 1948 letter to Heitler, he criticized Heitler's notion that the observer plays an important role in the process of wavefunction collapse:

> [I advocate] that one conceives of the ψ-function [i.e., wavefunction] only as an incomplete description of a real state of affairs, where the incompleteness of the description is forced by the fact that observation of the state is only able to grasp part of the real factual situation. Then one can at least escape the singular conception that observation (conceived as an act of consciousness) influences the real physical state of things; the change in the ψ-function through observation then does not correspond essentially to the change in a real matter of fact but rather to the alteration in *our knowledge* of this matter of fact. (emphasis in original) (Quoted in Harrigan and Spekkens, 2010)

Today it is widely thought that the (realist) ψ-epistemic view provides a straightforward resolution or even a dissolution of the measurement problem (see, e.g. Leifer, 2014).[1] In this paper, we will argue that this is not true.

Consider a quantum system being in the following superposition state:

$$|\psi\rangle = \sum_i c_i |a_i\rangle, \tag{1}$$

where $|a_i\rangle$ are the eigenstates of an arbitrary observable A, and c_i are the expansion coefficients. The Born rule tells us (and we also know by experience) that the result of a projective measurement of A is one of the eigenvalues of A, say a_i, with probability $|c_i|^2$. The collapse postulate in standard quantum mechanics further says that after the measurement the original superposition state instantaneously and discontinuously collapses to the corresponding eigenstate $|a_i\rangle$. The explanation of the collapse of the wave function provided by the ψ-epistemic view is as follows. Before the measurement, the observable A of the system has a definite value a_i. The superposition state we assign to the system reflects our incomplete knowledge about the actual value of the observable. Then after we measure the observable and know its actual value a_i, the superposition state will naturally be updated by the state corresponding to the value, $|a_i\rangle$.

[1] There is also another version of the ψ-epistemic view, which may be called the operationalist ψ-epistemic view. It regards the wave function of a quantum system as representing a state of incomplete knowledge about which outcome will occur if a measurement is made on the system. The objections given in this paper do not apply to this view.

Since this explanation of wavefunction collapse is supposed to hold true for the measurement of every observable at any time, it must assume that all observables defined for a quantum system have definite values at all times, which are their eigenvalues, independently of any measurement context, and moreover, measurements also reveal these pre-existing values. This means that the explanation is based on a hidden-variables theory of the most straightforward sort, which has been excluded by various no-go theorems. For example, the explanation assumes both value definiteness and noncontextuality for every observable. But the combination of these two assumptions violates the Kochen-Specker theorem (Kochen and Specker, 1967). The theorem requires that only a finite number of observables can have definite values independent of measurement context (in a Hilbert space of dimension $d \geqslant 3$).[2] Therefore, the above explanation of wavefunction collapse provided by the ψ-epistemic view, even if it is valid, can only be valid for a finite number of observables, and it is invalid for most observables which have no pre-existing values before a measurement.

This means that there are at least three problems the ψ-epistemic view needs to solve before solving the measurement problem. First of all, for those observables for which the above explanation of wavefunction collapse is valid, it needs to answer why these observables are special. If there are no plausible reasons, then all observables will have the same status and the explanation of wavefunction collapse for them will be the same. As a result, the above explanation will be invalid for all observables.

Next, in order that a ψ-epistemic model is consistent with the predictions of quantum mechanics, the underlying ontic state will be also changed during the collapse of the wave function in general. For example, in Spekkens's toy model (Spekkens, 2007), even a measurement of an eigenstate of the measured observable also causes change of the underlying ontic state. Thus, it seems that the measurement problem is not really dissolved by the ψ-epistemic view; rather, it turns to the question of why the underlying ontic state is changed during the collapse of the wave function. Only information update cannot explain this physical change.[3] This indicates that even if assuming the above explanation of wavefunction collapse is valid for some

[2]Here we ignore the finite precision loophole of the Kochen-Specker theorem, which allows non-contextual hidden-variables theories, but which is widely regarded as physically implausible (Barrett and Kent, 2004). Besides, we note that for a quantum system all observables can have their expectation values in the state of the system at all times (Gao, 2015). The Kochen-Specker theorem does not prohibit this, since the definite values being expectation values violates the production rule, which is one of the key assumptions of the theorem (Kochen and Specker, 1967).

[3]In Spekkens's (2007) toy model, this change is explained by the requirement of the so-called knowledge balance principle, which, roughly speaking, states that at most half of the information needed to specify the ontic state can be known at any given time. But again, the problem turns to explaining why there is this knowledge balance principle. For further discussion see Leifer (2014).

observables, there is still a further problem similar to the measurement problem which needs to be solved by the ψ-epistemic view.

Thirdly, for those observables which have no pre-existing values before a measurement, the measured superposition state admits of no epistemic interpretation, and the above straightforward solution to the measurement problem is not valid either. Then the ψ-epistemic view needs to find another solution to the measurement problem to explain the appearance of definite measurement results, which may probably be similar to the solutions provided by the ψ-ontic view.

Finally, we note that the ontological model framework (Harrigan and Spekkens, 2010; Pusey, Barrett and Rudolph, 2012), on which the existing ψ-epistemic models are based (Bartlett, Rudolph and Spekkens, 2012; Lewis et al, 2012; Aaronson et al, 2013), seems neither necessary nor sufficient to solve the measurement problem. The framework assumes that the underlying ontic state of a physical system determines the probabilities of different outcomes for a projective measurement on the system. In this way, the framework already excludes the deterministic solutions to the measurement problem such as the de Broglie-Bohm theory (and thus it is not necessary), while on the other hand, the framework does not explain the origin of the objective probabilities, as well as the appearance of definite measurement results (and thus it is not sufficient).

To sum up, we have argued that the collapse of the wave function cannot simply be explained as a process of updating information about the ontic state of the measured system, and thus the ψ-epistemic view does not provide a straightforward resolution of the measurement problem. Moreover, the ontological model framework, on which the existing ψ-epistemic models are based, also needs to be enlarged to solve the measurement problem.

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