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Essay review

The PBR theorem: Whose side is it on? ☆

Yemima Ben-Menahem

Department of Philosophy, The Hebrew University of Jerusalem, Mt. Scopus, Jerusalem 91905, Israel

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ABSTRACT

This paper examines the implications of the PBR theorem for the debate on the reality of the quantum state. The theorem seeks to undermine epistemic interpretations of the quantum state and support realist interpretations thereof, but there remains ambiguity about the precise nature of epistemic interpretations, and thus ambiguity about the implications of the theorem. The aim of this paper is to examine a radical epistemic interpretation that is not undermined by the theorem and is, arguably, strengthened by it. It is this radical interpretation, rather than the one assumed by the PBR theorem, that many epistemic theorists subscribe to. In order to distinguish the radical epistemic interpretation from alternative interpretations of quantum states–in particular, to distinguish it from instrumentalism–a historical comparison of different approaches to the meaning of quantum probabilities is provided. The comparison highlights, in particular, Schrödinger's work on the nature of quantum probabilities as distinct from probabilities in statistical mechanics, and the implications of this distinction for an epistemic interpretation of probability in the two areas. Schrödinger's work also helps to identify the difficulties in the PBR definition of an epistemic interpretation and is shown to anticipate the radical alternative that is not undermined by the theorem.

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Quantum mechanics (QM) is known to be a fundamentally probabilistic theory. As such, it raises questions about the interpretation of the concept of probability in its context. One of the alternatives that have attracted a great deal of attention in the last few decades is an epistemic interpretation (including information-theoretic or Bayesian interpretations), according to which quantum states (wave functions) represent states of knowledge or belief or information.[1] The recent PBR theorem purports to show that the epistemic interpretation is untenable. It is therefore taken to confirm a realist interpretation of quantum states, according to which the quantum state (wave function) represents the physical state of the system, or is at least a function of this physical state. It is this realist message that is the source of the theorem's attraction. A point sometimes missed, though noted by PBR and elaborated, for example, in Leifer (2014), is that one should distinguish between two kinds of epistemic interpretations: epistemic interpretations that presuppose a well-defined state of the system—its 'real' state—and epistemic interpretations that decline this assumption. Let us call the latter *radical* epistemic interpretations. Once the distinction is in place, it becomes clear that the theorem targets the former variant of the epistemic interpretation, not the radical version. Even those who are aware of the distinction, however, associate the radical interpretation with positivism or instrumentalism. They therefore give the impression that for non-instrumentalists the theorem does in fact rule out epistemic interpretations and leaves the realist interpretation as the only viable option. Examining the radical interpretation in light of the PBR theorem, I will show that the association with instrumentalism is unfounded and that the theorem makes room for a radical epistemic interpretation distinct from instrumentalism. Furthermore, we will see that it is the radical interpretation, rather than the one undermined by the theorem, that many of the leading epistemic theorists have in mind. My conclusion is therefore that rumors about the death of the epistemic interpretation were exaggerated. Along the way, I hope to clarify the following issues involved in the epistemic approach.

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E-mail address: yemima.ben-menahem@mail.huji.ac.il

[1] See, for example, Caves et al. (2001, 2002), Pitowsky (2006), Bub and Pitowsky (2010), Spekkens (2005).

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1. If, as the epistemic theorist has it, quantum states represent knowledge, or belief or information, what is the right way of completing this statement–knowledge (belief, information) about *what*?
2. What is the difference between current epistemic interpretations of QM and earlier interpretations of quantum probabilities, for example, the ensemble interpretation favored by Einstein?
3. What is the difference between an epistemic interpretation of probability in general, as applied in daily contexts, or in statistical mechanics, where it is also popular, and the epistemic interpretation of QM?

I will start with an outline of the PBR theorem (I) and then turn to the roots of the controversy over the meaning of quantum states in early debates about the probabilistic interpretation of the wave function (II). In section III, I examine Schrödinger's analysis (1935) of quantum probabilities, stressing, in particular, his critical response to Einstein's interpretation and the EPR paper. The argument here is that Schrödinger's analysis points to the radical epistemic interpretation, which differs from the epistemic interpretation assumed by the PBR theorem. I return to the lessons of the theorem, the issue of instrumentalism, and questions 1–3 in the concluding section (IV).

1. The PBR theorem

In their 2012 paper "On the reality of the quantum state", Pusey, Barrett and Rudolph summarize the no-go argument that has come to be known as the PBR theorem:

> We show that any model in which a quantum state represents mere information about an underlying physical state of the system, and in which systems that are prepared independently have independent physical states, must make predictions that contradict those of quantum theory. (Pusey et al., 2012, 475).

Clearly, the theorem purports to target the epistemic interpretation of the wave function, thereby supporting its realist interpretation. This is indeed the received reading of the theorem and the source of its appeal. Under the title "Get Real" Scott Aaronson (2012) announced the new result as follows:

> Do quantum states offer a faithful representation of reality or merely encode the partial knowledge of the experimenter? A new theorem illustrates how the latter can lead to a contradiction with quantum mechanics. (2012, p. 443).

Aaronson distinguishes between the question of whether a quantum state corresponds to different physical states and the PBR question—whether a physical state corresponds to different quantum states. It is the latter that the PBR theorem purports to answer in the negative (See Fig. 1).

> It is crucial to understand that we're not discussing whether the same wavefunction can be compatible with multiple states of reality, but a different and less familiar question: whether the same state of reality can be compatible with multiple wavefunctions. Intuitively, the reason we're interested in this question is that the wavefunction seems more 'real' if the answer is no, and more 'statistical' if the answer is yes (2012, p. 443).

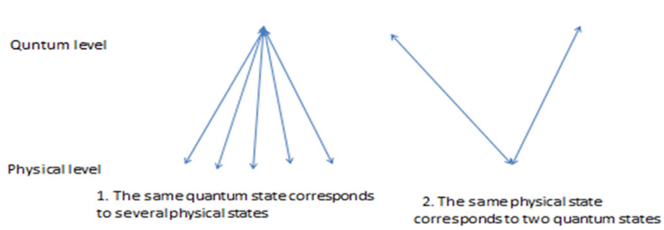

Fig. 1. Two kinds of relations between physical states and quantum states.

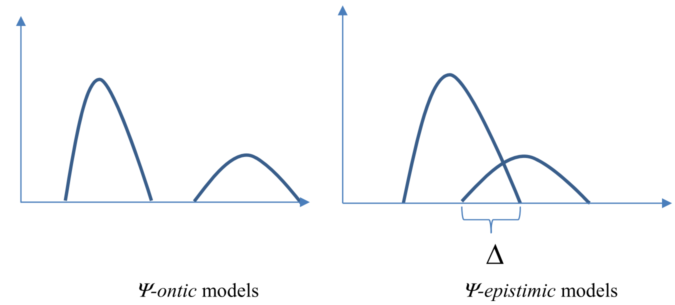

Fig. 2. The distinction between (probabilistic) ontic and epistemic models.

Since the PBR theorem does indeed answer the said question in the negative, the conclusion is that the wave function has gained (more) reality.

Why is the negative answer to this question a refutation of the epistemic interpretation? Here Pusey et al. build on a distinction between Ψ -ontic models and Ψ-epistemic models introduced by Harrigan and Spekkens (2010): In Ψ -ontic models the Ψ function corresponds to the physical state of the system; in Ψ-epistemic models, Ψ represents knowledge about the physical state of the system. Consequently, there are also two varieties of incompleteness: Ψ could give us a partial description of the physical state or a partial representation of our knowledge about that state. If a Ψ-ontic model is incomplete, it is conceivable that Ψ could be supplemented with further parameters – 'hidden variables'. In this case, the same Ψ function could correspond to various physical states of the system, distinguishable by means of the values of the additional hidden variables. Presumably, Ψ-epistemic models can also be complete or incomplete but completing them cannot be accomplished by hidden variables of the former kind. Note that this analysis presupposes an answer to question no. 1 (in the introduction to this paper)–what is the knowledge (belief, information) represented by the quantum state *about*? The answer given here is that it is knowledge about the physical state of the system. So far this is merely a terminological distinction, but Harrigan and Spekkens also offer a *criterion* that distinguishes Ψ-epistemic from Ψ-ontic models: If the Ψ function is understood epistemically, it can stand in a non-functional relation to the physical state of the system, that is, the same physical state may correspond to two different (non-identical but also not orthogonal) Ψ functions. Or, when probabilities rather than sharp values are considered, the supports of the probability distributions corresponding to different Ψ functions can overlap for some physical states (see Fig. 2).[2]

This possibility, they claim, only makes sense under the epistemic interpretation of Ψ, for it is conceivable that knowledge about the physical state could be updated without any change to the physical state itself. In short, a criterion for a model being Ψ-epistemic is precisely the possibility of such overlap of the supports of different probability functions. Getting ahead of my argument, I should stress that allowing such a non-functional relation between the physical state of the system and the quantum state, namely, allowing that the quantum state is not uniquely determined by the physical state, is a non-trivial assumption. In philosophical terminology, the ontic option illustrated in figure 1_1, where every physical state corresponds to a single quantum state is referred to as a relation of supervenience. (There is no supervenience in the reverse direction). In figure 1_2, however, illustrating

[2] Figure no. 2 follows the schematic illustration in the PBR paper.