

# Epistemic Separability and Everettian Branches – A Critique of Sebens and Carroll

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## Abstract

We discuss the proposal by Sebens and Carroll to derive the Born rule in Everettian quantum mechanics from a principle they call ‘ESP-QM.’ We argue that the proposal fails: ESP-QM is not, as Sebens and Carroll argue, a ‘less general version’ of an independently plausible principle ‘ESP’ and can only be motivated by the empirical success of quantum mechanics, including use of the Born rule. Therefore, ESP-QM cannot have the status of a meta-theoretical principle of reasoning and provides no viable basis for deriving the Born rule.

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## 1 Introduction

Proponents of the Everett interpretation of quantum theory continue to wrestle with the problem of justifying why rational agents in an Everett world should use the Born Rule when assigning probabilities to measurement outcomes. In the past few years, the most-discussed attempt to solve this problem has been the decision-theoretic approach championed by Deutsch and Wallace. Recently, Sebens and Carroll [2018] have argued for an epistemic approach, which gives a very straightforward account of quantum probabilities in terms of self-locating uncertainty in the Everettian ‘multiverse.’<sup>1</sup> This approach is consistent with the way probability is conceived as self-locating uncertainty in attempts to subject cosmological multiverse theories to empirical tests.

Sebens and Carroll claim to have solved the probability problem in Everettian quantum theory by deriving from a principle that they call ‘ESP-QM’

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<sup>1</sup>This general type of approach can be linked to (Vaidman [1998]).

(where ‘ESP’ stands for ‘epistemic separability principle’) the result that epistemic agents in the Everettian multiverse should align their self-locating credences with the branch weights obtained from the Born rule. ESP-QM, in turn, is motivated as the implementation, appropriate in the Everettian quantum context, of a more general principle that Sebens and Carroll call the Epistemic Separability Principle (ESP). ESP encodes the idea that an agent’s rational self-locating analysis cannot depend on parts of the universe that are known to be entirely unrelated to her observations. This, they argue, is an independently plausible assumption.

According to Sebens and Carroll, their result establishes that ‘the Born rule is the uniquely rational way of apportioning credence in Everettian quantum mechanics.’ (Sebens and Carroll [2018], abstract) Here we dispute this claim by arguing that Sebens and Carroll misrepresent what is accomplished by their derivation of the Born rule from ESP-QM. First, as we argue, ESP-QM should not be regarded as the implementation of ESP in the Everettian quantum context. There is no cogent step that leads from ESP to ESP-QM in a quantum physical context. Quite to the contrary, the rationale behind ESP may be taken to suggest self-locating credences that are in general at variance with ESP-QM. Second, absent its ESP-based motivation, the plausibility of ESP-QM depends entirely on the empirical success of quantum mechanics – and therefore, indirectly, on assuming the Born rule. There is no basis for viewing ESP-QM as an independently attractive principle of rational reasoning. Establishing that the Born rule can be derived from it does not solve the probability problem of Everettian quantum theory.

## 2 Everettian branch structure and the epistemic separability principle (ESP)

Everettian quantum mechanics can be viewed as a consistent and empirically applicable scheme even in the absence of any explanation as to why the Born rule prescribes the probability one should rationally assign to measurement outcomes. It is consistent to add the Born rule as a primitive independent rule to the dynamical equations of quantum mechanics.<sup>2</sup> The Born rule would in this case play the role of a recipe the physicist has to follow in order to extract empirical predictions from Everettian quantum mechanics. It would not represent a property of the world we aim to describe by Everettian quantum mechanics. Nor would it follow from any characteristics of Ever-

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<sup>2</sup>Since re-coherence effects render Everettian quantum mechanics empirically inequivalent to canonical quantum mechanics, Everettian quantum mechanics can be understood as a physically distinct alternative to canonical quantum mechanics on a strictly empiricist basis without any realist commitment to other branches. As Barrett [2011] points out, Everett himself viewed his theory along these lines.

ettian QM that represent properties of the world. This seems unsatisfactory to many (though by no means all) physicists and philosophers of physics. A number of proponents of Everettian QM have therefore aimed to explain the Born rule in a way that is responsive to the ontic commitments of Everettian quantum mechanics. Both the decision-theoretic programme championed by Deutsch [1999] and Wallace [2012] and the proposal by Sebens and Carroll fall into this category.

In order to put the idea proposed by Sebens and Carroll into context, it is helpful to start with a brief look at the decision-theoretic approach. According to Deutsch and Wallace, applying the Born rule is the only rational betting behavior open to an agent who endorses Everettian quantum mechanics. In this decision-theoretic sense, Deutsch and Wallace argue, the Born rule follows from Everettian quantum mechanics even though the Born weights do not represent any kind of probability of existence. One contentious aspect of this proposal is the need to introduce fairly specific and in some cases controversial rationality conditions that determine what it takes to bet rationally. One of those conditions is *diachronic consistency*, which enforces that rational betting on the next measurement outcome must not depend on the branching structure in that measurement's future. Sebens and Carroll reject diachronic consistency as a rationality criterion because, as they convincingly argue, it is violated in perfectly consistent arguments of self-location in well-defined multiverse setups.

Having rejected diachronic consistency, Sebens and Carroll suggest an alternative strategy for motivating the Born rule. Their approach follows Deutsch and Wallace in presupposing that a decoherent worlds structure can be relied upon when extracting the Born rule from Everettian quantum mechanics. This is itself a controversial assumption (see [Baker, 2007, Kent, 2010, Dawid and Thébault, 2015] for criticism), but we accept it for the purposes of this note. The Born rule is then extracted based on analyzing self-locating credences in an Everettian multiverse.

Sebens and Carroll start by introducing a general principle of rational self-locating belief, which they call the epistemic separability principle (ESP). The 'gist' of ESP is that '[t]he credence one should assign to being any one of several observers having identical experiences is independent of the state of the environment.' [Sebens and Carroll, 2018, 40] In other words, according to ESP an agent's rational self-locating credences depend only on the states of those subsystems  $S$  of the universe  $U$  that contain observers with internally qualitatively identical states as the agent's and not on the state of the rest of  $U$ . The full formulation of ESP is:

**ESP:** Suppose that [the] universe  $U$  contains within it a set of subsystems  $S$  such that every agent in an internally qualitatively identical state to agent  $A$  is located in some subsystem which is an element of  $S$ . The probability that  $A$  ought to assign to

being located in a particular subsystem  $X \in S$  given that they are in  $U$  is identical in any possible universe which also contains subsystems  $S$  in the same exact states (and does not contain any copies of the agent in an internally qualitatively identical state that are not located in  $S$ ). [Sebens and Carroll, 2018, 40]

$$P(X|U) = P(X|S) \tag{1}$$

Here the conditional probability  $P(X|U)$  is to be understood as the self-locating probability of being in subsystem  $X$ , given that one inhabits the universe  $U$ . Similarly,  $P(X|S)$  is the self-locating probability of being in the subsystem  $X$ , given that one inhabits one of the subsystems that are elements of  $S$ , not knowing which. For the sake of the argument, we will, in this paper, follow Sebens and Carroll in accepting ESP as a valid principle of rational reasoning.

Sebens and Carroll then make the claim that the self-locating credences of an epistemic agent in Everettian quantum theory conform to what they take to be a quantum version of ESP, which they call ‘ESP-QM.’ That principle states that the probability one should assign to being in a certain branch of an Everettian multiverse does not depend on the full quantum state  $\Psi$  of the universe, but only on the reduced density matrix  $\hat{\rho}_{AD}$  that describes the combined system of the agent  $A$  and the detector  $D$ :

ESP-QM: Suppose that an experiment has just measured observable  $\hat{O}$  of system  $S$  and registered some eigenvalue  $O_i$  on each branch of the wave function. The probability that agent  $A$  ought to assign to the detector  $D$  having registered  $O_i$  [in her branch] when the universal wave function is  $\Psi$ ,  $P(O_i|\Psi)$ , only depends on the reduced density matrix of  $A$  and  $D$ ,  $\hat{\rho}_{AD}$ :

$$P(O_i|\Psi) = P(O_i|\hat{\rho}_{AD}) \tag{2}$$

Using an argument idea adapted from [Zurek, 2005], Sebens and Carroll show that ESP-QM entails the Born Rule as the uniquely correct prescription for assigning self-locating probabilities. Since, according to them, ESP-QM is the rational principle for assigning self-locating credences in Everettian quantum theory, they regard this result as solving the long-standing probability problem of the Everett interpretation.

Sebens and Carroll argue their case for ESP-QM based on a specific example of a quantum process, which they call the Once-or-Twice example.

In Once-or-Twice, Alice and Bob each have a spin-1/2 particle both of which have been prepared in the  $x$ -spin up eigenstate. Alice measures spin in  $z$ -direction of her particle without looking at the outcomes yet, but Bob does look at the outcome and measures spin in  $x$ -direction of his particle if the outcome of Alice’s measurement was  $+1/2$ . On Sebens and Carroll’s

view of Everettian QM, branching occurs across the entire wave function if and when Bob makes his measurement. Therefore, inasmuch as branches are precisely defined, after Bob’s measurement there are two branches in which Alice’s outcome is  $+1/2$ , but only one branch in which it is  $-1/2$ . Branch counting<sup>3</sup> thus recommends that Alice ascribe probability  $2/3$  to being in a  $+1/2$ -branch, whereas the Born rule recommends ascribing probability  $1/2$ . Branch counting thus is at variance with the Born rule in the given case.

Sebens and Carroll now argue that ESP-QM is a ‘less general version of ESP’ [Sebens and Carroll, 2018, p. 42] that can offer guidance as to what should replace branch counting as the adequate strategy of extracting probabilistic claims from Everettian quantum physics. The role of ESP was to specify a universal independence assumption in a classical context. In a quantum context, they argue, the core independence principle is related to the reduced density matrix: if we consider a quantum experiment with outcomes X and Y that is characterized by a given reduced density matrix, the probability of being in branch X must be the same in any universe with that same reduced density matrix. This implies that self-location probabilities on Everettian branches must be independent of any part of the universe beyond the reduced density matrix that describes a given quantum decision. Therefore, Bob’s measurement cannot influence Alice’s assessment of the probabilities of the outcomes of her measurement.

Sebens and Carroll argue that this point of view is in agreement with our intuitions in the Alice case. The state (reduced density operator  $\rho_{AD}$ ) of the Alice + Detector system is unchanged when Bob performs his measurement on the branch in which the spin in  $x$ -direction of Alice’s particle is  $+1/2$ . They suggest that it seems highly counter-intuitive to assume that Alice’s probability assessments should change due to an event that does not change the state of the Alice + Detector system.

Sebens and Carroll conclude that ESP-QM is the appropriate implementation of ESP in the quantum context that can provide a basis for deducing the Born rule once the truth of Everettian QM is assumed.

### **3 Why ESP-QM is not ‘a less general version of ESP’**

Sebens and Carroll’s line of reasoning relies on two assertions. First, they state that ESP-QM is a ‘less general version of ESP’, which allows them to use the plausibility of ESP as a reason for endorsing ESP-QM in the case of quantum processes. Second, they assert that ESP-QM as a principle of self-location has the character of a general principle of reasoning and

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<sup>3</sup>Branch counting means identifying and counting the decohered branches of the wave function and aligning one’s self-locating credence about being in a branch with a particular property with the ratio of branches with that property.

thus amounts to more than a specific physical posit that needs to be added to Everettian QM for the sake of empirical adequacy. If ESP-QM simply amounted to a physical posit, Sebens and Carroll’s claim that the Born rule can be deduced from ESP-QM based on Everettian QM would deflate to the unsurprising statement that the Born rule can be added to Everettian QM as an additional posit. In the following we will contest both of these assertions.

Let us start the analysis by looking at the way ESP plays out in Once-or-Twice in a little more detail. We consider the situation both before and after Bob makes his measurement. At  $t_2$ , immediately after Alice’s measurement but before Bob’s, the universal wave function  $\Psi(t_2)$  is given by

$$\Psi(t_2) = 1/\sqrt{2}\psi_{AD,+}\chi + 1/\sqrt{2}\psi_{AD,-}\chi. \quad (3)$$

where  $\psi_{AD,+}$  and  $\psi_{AD,-}$  are the states of the Alice + Detector system before Alice’s registering the measured result in the different branches, and the state  $\chi$  describes the rest of the universe, including Bob before making his measurement (see Eq. (7) in Sebens and Carroll [2018] for more complete decompositions of  $\Psi$  at all times).

Next, at  $t_3$ , after Bob’s measurement but prior to Alice’s looking at her measurement outcome, the universal wave function is

$$\Psi(t_3) = 1/2\psi_{AD,+}\chi_{+,+} + 1/2\psi_{AD,+}\chi_{+,-} + 1/\sqrt{2}\psi_{AD,-}\chi_{-,x}. \quad (4)$$

where the states  $\chi_{+,+}$ ,  $\chi_{+,-}$ , and  $\chi_{-,x}$  are the associated states of the rest of the universe including Bob.

At  $t_2$ , the self-locating problem for Alice is most naturally construed as concerning the system  $S$  that consists of her copies in the two branches corresponding to the two states  $\psi_{AD,+}$  and  $\psi_{AD,-}$ . Now, for ESP to have any specific implications for the transition from  $t_2$  to  $t_3$ , one would have to make sure that, at  $t_3$ , the system with respect to whose subsystems Alice has self-locating uncertainty is still the same  $S$ . If not, the self-location problem at  $t_3$  concerns a different set  $S'$  and ESP provides no basis for comparing self-location credences before and after Bob’s measurement.

We will now make three points which demonstrate in conjunction how what Sebens and Carroll have accomplished fails to solve the probability problem for Everettian quantum theory.

**1: ESP-QM is not a systematically preferred Everettian quantum version of ESP.**

ESP takes the form of ESP-QM if one identifies the ‘set of subsystems  $S'$  that appears in ESP with the system’s reduced density matrix  $\rho_{red}$ , which is obtained from the total global quantum state by performing the trace over the degrees of freedom of all other systems. Sebens and Carroll motivate this move in an appendix to the paper. There they appeal to the requirement for considering something to be the state of a subsystem of the universe that it

should (i) together with the states of all other subsystems and facts about the connections between the subsystems, yield the total state, and (ii) be sufficient to determine its own evolution when the subsystem is isolated. [Sebens and Carroll, 2018, 67]

In a further argumentative step, Sebens and Carroll argue that the reduced density matrix satisfies this criterion: facts about how the subsystem state is entangled with the state of the rest of the universe are attributed to how those states are ‘connected.’ But even if one accepts both the stated requirement and the claim that the reduced density matrix satisfies it, one can still question, as Sebens and Carroll acknowledge, whether it does so uniquely. Notably in the context of Everettian QM one may prefer a notion of physical subsystem state which includes information about whether the system undergoes branching. The reduced density matrix does not in general do that. As we argue in what follows, this makes it an odd candidate for representing (the complete states of) subsystems  $S$  in ESP-like reasoning in the context of Everettian QM.

**2: Based on the rationale behind ESP, one can motivate self-locating credences in Everettian QM that are generally in conflict with ESP-QM.**

Sebens and Carroll endorse a conception of Everettian branching according to which ‘branching happens throughout the whole wave function’ [Sebens and Carroll, 2018, 34] whenever it happens.<sup>4</sup> As they explain, this conception entails that ‘[t]he change from  $t_2$  to  $t_3$  in Once-or-Twice increases the number of copies of Alice in existence’ [Sebens and Carroll, 2018, p. 46]. Presumably, this increase in the number of copies of Alice corresponds to a physical change in the Alice + Detector system. Since the reduced density matrix  $\rho_{AD}$  of the Alice + Detector system does not change, this conception is in tension with the idea—underlying ESP-QM—that the reduced density matrix is to be regarded as the physical state of a system.

Worse, regarding the increase of copies of Alice in existence as irrelevant to Alice’s rational self-locating credences conflicts with the motivation that Sebens and Carroll themselves give for ESP in the first place. In their considerations on the Dr. Evil scenario they acknowledge that Dr. Evil’s self-locating credences may reasonably change ‘if what’s happening on Neptune includes another copy of the laboratory with another duplicate Dr. Evil in it. If there’s a duplicate on Neptune, Dr. Evil can no longer be sure that Neptune is in fact a distant planet and not the one under his feet (and thus cannot treat it as irrelevant to his probability assignments).’ Now, if the Dr. Evil scenario is in any way relevant as an analogy to Once-or-Twice,

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<sup>4</sup>This view has been criticised in (McQueen and Vaidman [2019]) as implausible. But we adopt it in this paper in order to demonstrate a more general problem the approach by Sebens and Carroll faces even if one concedes them this assumption.

as Sebens and Carroll, clearly suggest, it seems obvious to suggest that an analogous duplication process, with analogous consequences for rational self-locating credences, occurs and affects Alice when she undergoes Everettian branching as a result of Bob’s measurement at  $t_3$ . But this means that the set  $S$  of subsystems with respect to which Alice has self-locating uncertainty changes at  $t_3$  to some  $S' \neq S$ . ESP by itself thus does not sanction the verdict—which indeed follows from ESP-QM—that Bob’s measurement has no effect on Alice’s rational self-locating credences. By the standards of the rationale behind ESP, as provided by Sebens and Carroll themselves, the ESP-QM-based verdicts are not in general plausible.

Since ESP does not specify the way in which self-location within the new system  $S'$  must be carried out, it does not rule out that Alice’s self-locating credences in Once-or-Twice are the same at  $t_2$  and  $t_3$ . ESP by itself is simply silent with respect to whether Alice’s credences should change after Bob’s measurement. It does not strictly speaking determine whether Alice must rely on branch counting (inasmuch as defined) or the Born rule or some other strategy when assigning her self-locating credences.<sup>5</sup> But in view of the motivation that Sebens and Carroll themselves give for adopting ESP, the recommendations issued based on ESP-QM do not in general appear to be a natural choice.

According to points 1 and 2, ESP-QM is neither a less general version of ESP nor a replacement of ESP in an Everettian context. In fact, the two principles have different types of implications for rational self-location in Everettian QM. ESP imposes constraints on self-locating credences in situations that agree on the system  $S$  with respect to whose subsystems self-locating credences are assigned; but it remains silent with respect to the specific probabilistic weights attributed to any subsystem of  $S$  (be they agents on different branches or on one and the same branch). ESP-QM, to the contrary, remains silent about self-location on one branch but does specify rational credences to be assigned to agents on different branches, stating that they correspond to the Born weights of branches. Therefore, most implications of ESP-QM are not implications of ESP and most implications of ESP are not implications of ESP-QM. ESP-QM is simply an entirely different principle than ESP.

**3: ESP-QM has no independent motivation as a principle of self-location in Everettian QM beside the fact that the Born rule can be extracted from it.**

With the idea of regarding ESP-QM as a ‘less general version of ESP’ off the table, there could still be another, independent, motivation for ESP-QM

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<sup>5</sup>Sebens and Carroll acknowledge this point. In cases where they want to adhere to the principle of indifference, they appeal to a variant of ESP that they call ‘Strong ESP’ [Sebens and Carroll, 2018, 48], which entails that ESP reduces to self-locating indifference when applied to within-branch self-locating uncertainty



as a principle of rational self-locating credences in Everettian QM.

Sebens and Carroll offer a second argument for the principle's cogency by pointing out that endorsing the principle seems to be the only way of getting self-location probabilities off the ground in Everettian QM, since branch identities are fuzzy and branch counting appears to be conceptually impossible. But even if one is willing to concede that no other prescriptions for assigning self-locating beliefs to branches can be coherently formulated, this does not establish ESP-QM as a principle of reasoning.

Whether or not a theory allows for the the extraction of self locating probabilities, probabilities of measurement outcomes, or other relevant features, depends on that theory's conceptual structure. If a theory fails to provide such desired kinds of information, this may be a reason for replacing the given theory by an alternative that does the job. If it is possible to extend the given theory in a way that provides the desired kinds of information, such an extension may be a way to go. In the case of Everettian QM, as discussed above, adding the Born rule to the theory as a primitive rule would be a step of this kind. The described process fully plays out at the level of scientific theory building.

There is no basis, however, for invoking a new principle of reasoning for the mere reason that such a principle would increase a given theory's range of analytic implications or its predictive power. Any attempt to do so indicates a misunderstanding of the relation between a scientific theory and principles of reasoning. In the final Section, we will have a closer look at this issue.

## 4 What is a principle of reasoning?

Adherents of a 'rationality principle' approach to Everettian QM, such as Deutsch and Wallace or Sebens and Carroll, acknowledge that Everettian QM does not allow for the deduction of objective probabilities of measurement outcomes. Moreover, they feel discontent with simply introducing the Born rule as a primitive instrumentalist principle. The proposed way out is to open up the additional playing field of requirements of rational reasoning in the given context. Those requirements are then claimed to enforce the application of the Born rule once one assumes that Everettian QM is true. While Deutsch and Wallace focus on rational betting, Sebens and Carroll focus on principles of self-locating reasoning.

The proposed principles of rational reasoning have a peculiar status. On the one hand, they obviously cannot be strictly analytic. If they were, implementing them in the given case would simply amount to logically deducing the Born rule from the Everettian branching structure. As just pointed out, the proponents of those principles agree that this is not possible. Sebens and Carroll explicitly call their principles 'epistemic.'

On the other hand, the requirements cannot be contained in the set of posits that define the theory of Everettian QM. Otherwise endorsing the principles would amount to introducing the Born rule as a primitive posit in the theory, which is not what exponents of the ‘rationality principle’ approach want to do.

When Sebens and Carroll suggest that the described extra-theoretical non-analytic criteria should be established in the context of self-location on Everettian branches, they can refer to the parallel case of self-location in a cosmic multiverse, where an equivalent role of general principles of reasoning is widely (though not universally) acknowledged. In the latter case, a cosmological theory  $T$  asserts a certain structure of the universe. Based on  $T$ , general principles such as the principle of indifference or ESP tell us how we should assess the probability that we sit in a given corner of the universe. Those principles are indeed neither analytic principles nor strictly implied by the cosmological theory  $T$ . So, in the context of the cosmological multiverse, they do play the role envisioned by Sebens and Carroll.

Sebens and Carroll can also rightfully argue that the principle of indifference must fail as a general principle of self-location in an Everettian context: it is inapplicable due to the impossibility of branch counting in a full Everettian branching structure. Sebens and Carroll can thus plausibly claim that ESP, which does not face this problem, should be kept and the principle of indifference should be abandoned when analysing Everettian branches. But this does not amount to a solution of the probability problem since, as spelled out in the previous section, ESP does not dictate any assignment of self-locating probabilities in concrete quantum scenarios like Once-or-Twice.

But, as we have seen in the previous section, there is just no way to motivate ESP-QM, which prescribes specific credences, from ESP, which does no such thing. Of course one still has the option to simply propose ESP-QM as a new principle of self-location that is specifically tailored to the context of Everettian quantum physics. However, introducing a new principle in that way is an entirely different conceptual move than appealing to an independently motivated general principle of reasoning such as ESP or the principle of indifference and motivating ESP-QM from there.

Principles like indifference or ESP work in the context of cosmology based on our general understanding that their application gives satisfactory results in a wide range of contexts that include the analysis of that theory’s implications but are by no means confined to the context of the given cosmological theory. Their validity as general principles of self-location that can be applied ‘from the outside’ when analysing a scientific theory’s implications crucially relies on the fact that they are not licensed exclusively by that same scientific theory.

ESP-QM cannot possibly meet this condition. It emerges in a specific

theoretical context where one general principle of reasoning, the principle of indifference, is in general inapplicable. Any principle that replaces it must be extracted from the very theoretical context that rendered the principle of indifference obsolete. Therefore, the new principle cannot be a general principle of reasoning of the kind exemplified by indifference or ESP. Rather, it is a principle that gets extracted from the theory itself. Since, as discussed above, the connection between Born weights and self-location does not follow from Everettian branching structure itself, ESP-QM thus can only be established once the posit of the Born rule has been assumed as a primitive principle of Everettian QM.

So, given that ESP-QM cannot be acknowledged as a principle of reasoning, what status could be attributed to it? ESP-QM does formally reach beyond the simple posit of the Born rule: it spells out how probabilities of self-location in Everettian branches would have to be specified in agreement with the Born rule. If a realist view of Everettian branches that was consistent with the Born rule could be developed, ESP-QM would describe the self-locating aspect of such a realist interpretation. But ESP-QM itself does not provide such a realist interpretation because it addresses only prescriptions for an agent's credences rather than the physical world itself. As long as the Born rule is merely introduced as a primitive rule, however, which, as suggested earlier in this paper, enforces an instrumentalist take on Everettian QM, ESP-QM merely amounts to a formal exercise. It defines a formal property called 'self-location probability' that couches the Born rule in the terminology of self-location but lacks any physical or realist significance.

Either way, Sebens and Carroll's discussion of ESP and their derivation of the Born rule from ESP-QM, while stimulating and illuminating, does not resolve the probability problem for Everettian quantum theory.

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