

PURE QUANTUM INTERPRETATIONS ARE NOT VIABLE

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ABSTRACT. Pure interpretations of quantum theory, which reject the classical part of the Copenhagen interpretation without adding new structure to it's quantum part, are not viable. This is a consequence of a non-uniqueness result for the canonical operators.

1. INTRODUCTION: THE NON-UNIQUENESS OF THE CANONICAL STRUCTURE

In [15] we have proven two non-uniqueness theorems: For some fixed Hamilton operator \hat{h} , we have constructed for some continuous parameter s different pairs $\hat{q}(s)$, $\hat{p}(s)$ of canonical operators so that $\hat{h} = \frac{1}{2m}\hat{p}(s)^2 + V(\hat{q}(s), s)$ with physically different, but equally nice potentials. In addition, we have constructed different tensor product structures (or “decompositions into systems”) so that \hat{h} has an equally nice, but physically different representation of type $\hat{h} = \sum \frac{1}{2m_i}\hat{p}_i(s)^2 + V(\hat{q}(s), s)$ in all or them. We have considered the consequences of this construction for the applications of decoherence in fundamental physics: The belief about the ability of decoherence to define the classical limit without additional structure have to be given up. To postulate some fundamental decomposition into systems which would allow to derive a preferred basis we have rejected because the losses related with an emergent Q (uncertainty, dependence on dynamics) are not compensated by gains in explanatory power.

The aim of this paper is to continue the consideration of the consequences. First, we reject the proposal to embrace the different $\hat{q}(s)$, $\hat{p}(s)$ as many different but equally real worlds. Then we argue that the whole Everett program, as well as the general hope to get rid of the classical Copenhagen part without adding new structure to the quantum part, has to be given up: The removal of the classical Copenhagen part requires new structure, sufficient to fix one canonical structure. This removes one of the main advantages of the Everett program – its purity – and endangers its symmetry properties. In particular, the popular argument that “[P]ilot-wave theories are parallel-universe theories in a state of chronic denial” [6] becomes invalid.

2. WHAT IS WRONG WITH A “MANY WORLDS”-LIKE SOLUTION

Anticipating a possible non-uniqueness of the construction of a preferred basis, Saunders [14] has proposed a solution which avoids the introduction of new physical structure: One could accept the non-uniqueness and consider all the different classical limits defined by different $\hat{p}(s)$, $\hat{q}(s)$ as equally real different worlds. Brown and Wallace [5] describe this idea in the following way:

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Suppose that there were several such decompositions, each supporting information-processing systems. Then the fact that we observe one rather than another is a fact of purely local significance: we happen to be information-processing systems in one set of decoherent histories rather than another. [5]

Fortunately, the fact that the different $\hat{p}(s)$, $\hat{q}(s)$ define physically different worlds, even with different classical limits $H(p, q, s) = \frac{1}{2m}p^2 + V(q, s)$, allows a counterargument: Once all worlds are equally real, the physical properties of our particular world cannot be further restricted by Ockham's razor or further symmetry principles. These principles allow to restrict only theories about what really exists. All the really existing worlds are on equal footing, and to restrict the choice among them we can use only anthropic considerations.

But anthropic considerations cannot give exact answers. The subset of worlds which allow information-processing systems will be an open subset, containing together with our actual world also some of its environment. Our construction gives a continuous dependence of the parameter $s \in \mathbb{R}$.¹ Thus, the subset of worlds which allow information-processing systems will contain a non-trivial environment of our world. Our world has to be a generic element of this set.

Now let's look at what is physically different in the different worlds. We find that the eigenvalues of the eigenstates of \hat{h} remain fixed. But the expectation value of the positions for these eigenstates obviously depend not only on \hat{h} , but also on \hat{q} . Thus, for different choices of the $\hat{q}(s)$ we have to expect different expectation values for positions of the eigenstates.

Let's compare this with the physics of our world. Already in the simplest application of quantum theory, the hydrogen atom, we use a very special potential $V(q) = 1/|q - q_0|$. This choice fixes the position of the eigenstates relative to q_0 in an extremely symmetric way, far away from a generic choice. This would be an unexplainable coincidence if all the other, less symmetric potentials would also describe really existing worlds. Thus, this proposal has to be rejected (at least for potentials like $V(q) = 1/|q - q_0|$) because this theory is too symmetric, too beautiful for this proposal.

3. PURE INTERPRETATIONS ARE NOT VIABLE

The consequence of the impossibility to embrace all $\hat{p}(s)$, $\hat{q}(s)$ as describing real worlds is that one needs a mechanism which makes a certain choice of the \hat{p} , \hat{q} . One possibility is defined by the Copenhagen interpretation, which defines the correct operators by associating them with descriptions of experimental arrangements described in classical language.

Now, this "classical part" of the Copenhagen interpretation has been widely considered as unsatisfactory, and has motivated attempts to get rid of it. The ideal solution would be a derivation of the classical part from the quantum part taken alone. An interpretation of this type, which reject the classical part of Copenhagen and start with the pure quantum part, without introduction of additional structure, we call *pure interpretation*, even if they are in fact only programs for developing

¹ There exist, in fact, an infinite set of such continuous parameters s_1, s_2, \dots which, taken together, form an infinite-dimensional family of integrable systems [1], and the construction of [15] can be extended to all of them, so that we obtain an infinite-dimensional set.

such an interpretation. The most popular example is the Everett interpretation, described by Everett in the following way:

“This paper proposes to reward pure wave mechanics . . . as a complete theory. It postulates that a wave function that obeys a linear wave equation everywhere and at all times supplies a complete mathematical model for every isolated physical system without exception. . . . The wave function is taken as the basic physical entity with no a priori interpretation. Interpretation only comes after an investigation of the logical structure of the theory. Here as always the theory itself sets the framework for its interpretation. . . . The new theory is not based on any radical departure from the conventional one. The special postulates in the old theory which deal with observation are omitted in the new theory. The altered theory thereby acquires a new character. It has to be analyzed in and for itself before any identification becomes possible between the quantities of the theory and the properties of the world of experience.”
[7]

But it is not the only one. Another is Mermin’s “Ithaca interpretation” [12]: On the one hand, Mermin claims that “. . . I would like to have a quantum mechanics that does not require the existence of a classical domain” and introduces as one of the desiderata “The concept of measurement should play no fundamental role”. On the other hand, we read that “. . . by quantum mechanics I mean quantum mechanics as it is – not some other theory in which the time evolution is modified by non-linear or stochastic terms, nor even the old theory augmented with some new physical entities (like Bohmian particles) which supplement the conventional formalism without altering any of its observable predictions.”

Now, once these pure interpretations reject the classical domain of the Copenhagen interpretation, they lose, consequently, the Copenhagen way to solve our non-uniqueness problem. The “correct” operators \hat{p} and \hat{q} can no longer be distinguished among the $\hat{p}(s)$, $\hat{q}(s)$ by a postulated association with specific experimental arrangements described in classical language. On the other hand, pure interpretations refuse to add some replacement, some new, additional structure which would allow to compensate for the loss. Thus, they are forced to identify the “correct” choice of the \hat{p} , \hat{q} from the quantum part.

3.1. The pure quantum part of Copenhagen is not enough. In principle, one could imagine that the physical differences between the operators $\hat{h} = \frac{1}{2m}\hat{p}(s)^2 + V(\hat{q}(s), s)$ could be used to distinguish one as preferred. But the resulting theory would be physically quite different from the Copenhagen interpretation: Indeed, in the Copenhagen interpretation any of the Hamilton operators $\hat{h} = \frac{1}{2m}\hat{p}(s)^2 + V(\hat{q}(s), s)$ defines a valid quantum theory, physically different from the others, with an unproblematic classical limit $H(p, q, s) = \frac{1}{2m}p^2 + V(q, s)$. In an interpretation without additional structure which prefers one of them, we could obtain only one of the $H(p, q, s) = \frac{1}{2m}p^2 + V(q, s)$ as the classical limit of a quantum theory. Thus, almost all classical Hamiltonians would define classical theories which cannot be quantized, cannot be obtained as a classical limit of some quantum theory, despite having the nice standard form $H(p, q) = \frac{1}{2m}p^2 + V(q)$ with a nice smooth and localized potential $V(q)$.

Thus, such a theory would be very different from standard quantum theory, too much to be classified as an interpretation of quantum theory. Thus, we have to reject this idea.

3.2. Simple labels are not sufficient. A more plausible solution is to continue what has been done before: Namely, the definition of the operators \hat{p} and \hat{q} is left to the particular quantum theory, but the interpretation simply remains silent about the physical meaning of these definitions. They are simply taken as given.

But this is justified only in the context of the Copenhagen interpretation, where the operators \hat{p} and \hat{q} have a physical meaning defined by the descriptions of experimental arrangements. Even if the particular descriptions are usually not given, with a reference to common knowledge, they are assumed to be given. Thus, the operators \hat{p} and \hat{q} are distinguished physically. But without the classical Copenhagen part, this physical meaning disappears, thus, the denotations \hat{p} and \hat{q} are reduced to pure labels, without physical content.

But pure labels are certainly not sufficient. If the theory would be well-defined, we would have a well-defined classical limit too. The classical limit is something derived from the theory. But such a derivation cannot depend on simple labels without physical content. Thus, theories where different $\hat{p}(s)$, $\hat{q}(s)$ would be labeled \hat{p} and \hat{q} would nonetheless lead to the same classical limit. Instead, in the Copenhagen interpretation they have different classical limits $H(p, q) = \frac{1}{2m}p^2 + V(q)$. Thus, the pure interpretation would not be another interpretation of the same theory, but a different theory.

3.3. Properties of the new structure. As a consequence, one really needs an additional structure, which is not part of the Copenhagen interpretation, to compensate for the loss of the classical Copenhagen part. Pure interpretations, which refuse to do this, are not viable.

Some other, non-pure interpretations may become invalid too, if their additional structure is not sufficient to solve the non-uniqueness problem. Therefore it seems worth to distinguish some properties of this additional structure: The first and most obvious one is that it should be sufficient to distinguish one set of canonical operators among the $\hat{p}(s)$, $\hat{q}(s)$.

But it seems worth to distinguish also another property of the new structure: The new structure should be more important than a pure label. In particular, it should be important enough to influence the classical limit of the theory. Different choices of the new structure should lead to different classical limits.

3.4. Examples. These requirements are not too high – they are fulfilled, in particular, by theories of pilot wave type [2, 13], where we always have an explicit trajectory $q(t) \in Q$, which becomes the classical trajectory in the classical limit, and by physical collapse theories [9, 8], where the collapse localizes the wave function in a fundamental, predefined configuration space Q , which gives in the classical limit a trajectory in this particular configuration space. Above types of theories distinguish a configuration space Q physically, and it is this preferred configuration space which becomes, in the classical limit, the classical configuration space.

Note that what the non-uniqueness result proves is only that one needs some additional fundamental physical structure. This structure may be not directly connected with some configuration space. An example is a fundamental decomposition $\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$ into physically different subspaces, for example into fermions and

bosons, as considered by Kent [11]. The application of decoherence techniques or Schmidt decomposition may then lead to a preferred basis in \mathcal{H}_A . Some arguments against such a construction have been presented in [15], but they don't show that the interpretation is invalid.

Instead, consistent histories [10] provides a negative example. While it rejects the classical Copenhagen part (“The interpretive scheme which results is applicable to closed (isolated) quantum systems, . . . has no need for wave function ”collapse,” makes no reference to processes of measurement (though it can be used to analyze such processes) . . .” [10]), it adds something to the quantum formalism: “. . . an extension of the standard transition probability formula of nonrelativistic quantum mechanics to certain situations, we call them ”consistent histories,” in which it is possible to assign joint probability distributions to events occurring at different times in a closed system without assuming that the corresponding quantum operators commute.”

But this additional structure is quite general, and nothing suggests that one or another form of consistency condition would allow to distinguish one of the canonical structures among the $\hat{p}(s)$, $\hat{q}(s)$. Thus, consistent histories is another example of an interpretation which becomes invalid in the light of our non-uniqueness result.

4. CONSEQUENCES OF THE LOSS OF PURITY

Even if one accepts that one needs additional structure to solve the non-uniqueness problem, one may decide that particular attempts to develop pure interpretations have their own value and should not be given up, even if the initial hope to obtain a pure interpretation cannot be realized. This seems sociologically plausible in particular for the Everett program.

What would be the consequences? Most importantly, the previously poor interpretation would lose its most attractive property – its purity.

An example of an application of purity is the argument that “[P]ilot-wave theories are parallel-universe theories in a state of chronic denial” [6] which is quite popular in the many worlds community [19, 4, 17] would become invalid: The argument is that all what is real in many worlds – the wave function – is also real in pilot wave theory, and once it follows the same equation – the Schrödinger equation – the whole many worlds interpretation is part of pilot wave theories. Therefore, all the “many worlds” which, according to many world theory, really exist, have to exist in pilot wave theory too.

But this depends on the purity of the Everett interpretation. If we save many worlds by the introduction of some additional structure, the argument has to be reconsidered: If the new structure is not postulated in pilot wave theory too, the argument fails. To fix the choice of \hat{q} among the $\hat{q}(s)$ with some structure which is part of pilot wave theory, one has no other choice as to introduce at least the configuration space itself. But, as we have already discussed, the new structure needs some physical content, the pure label “this is the correct configuration space Q ” is not sufficient. If this physical content would be an actual configuration, then we would have obtained a variant of pilot wave theory instead of many worlds. If it is something else, the argument fails again.

But this may be not the only loss. One of the major arguments in favour of many worlds as well as of other pure interpretations is their claimed compatibility

with relativistic symmetry.² But whatever the additional structure, it may restrict the symmetry group of the theory. In particular, the configuration space itself – the structure defined by the operator \hat{q} we have to choose among the $\hat{q}(s)$ – is (at least in its usual form) not covariant. The danger that some additional structure will destroy relativistic symmetry is recognized, for example, by Wallace, who notes that “...there seems to be no relativistically covariant way to define a world ...” [17].

5. DISCUSSION

We have shown that the only way to handle our non-uniqueness result is to make a choice among the $\hat{p}(s)$, $\hat{q}(s)$, and to justify this choice by some physical structure which can distinguish the true \hat{p} , \hat{q} . It follows that a quantum interpretation which does not embrace the classical part of the Copenhagen interpretation needs additional structure. One can try to save the pure interpretations by adding such a structure. But what would be the motivation for doing it? The most attractive feature of the pure interpretations – the absence of additional structure – will be lost anyway.

It was not the aim of the paper to present a complete overview over all the proposed interpretations of quantum theory which become unviable in the light of our non-uniqueness problem. The examples we have found to be invalid – the Everett, Ithaca, and consistent histories interpretations – are important enough to illustrate that every interpretation of quantum theory has to be evaluated in the light of our non-uniqueness result.

This evaluation has to consider how the non-uniqueness problem is solved in the given interpretation. It has to be shown that it prefers one canonical structure \hat{p} , \hat{q} among the $\hat{p}(s)$, $\hat{q}(s)$. Moreover, this preference should play a sufficiently important role in the classical limit: Different choices of \hat{p} , \hat{q} should lead to different classical limits.

We have also found examples of theories which solve the non-uniqueness problem: Pilot wave theories and physical collapse theories. Above kinds of theories assign an explicit physical role to the configuration space Q , or as the space containing the explicit configuration $q(t) \in Q$, or by the explicit modification of the Schrödinger equation which localizes the wave packets in Q . In above cases, it is obvious that this solves the non-uniqueness problem.

The main lesson is that that quantum theory needs more than a wave function guided by some Hamilton operator: It needs some additional physical structure which gives the canonical operators \hat{p} and \hat{q} a physical meaning. As a consequence, what has been the main argument against theories of pilot wave type becomes their strongest advantage: The trajectory $q(t) \in Q$ is now a nice and simple candidate for the additional structure which is necessary anyway.

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² Given that a preferred frame allow a simple explanation of the SM fermions and gauge fields in terms of a condensed matter model [16], relativistic symmetry does not seem to have any fundamental importance.

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