Is the Universe a Quantum System?

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In order to relate the probabilistic predictions of quantum theory uniquely to measurement results, one has to conceive of an ensemble of identically prepared copies of the quantum system under study. Since the universe is the total domain of physical experience, it cannot be copied, not even in a thought experiment. Therefore, a quantum state of the whole universe can never be made accessible to empirical test. Hence the existence of such a state is only a metaphysical idea. Despite prominent claims to the contrary, recent developments in the quantum-interpretation debate do not invalidate this conclusion.

I. INTRODUCTION

A hundred years after Planck’s quantum hypothesis, quantum theory seems to be universally valid. While it has its roots in the atomic and subatomic domain, the stability of matter, diamagnetism and superconductivity are examples of quantum effects in the macroscopic domain. A fundamental limitation on the applicability of quantum theory has not been accepted so far. The formalism of general quantum theory allows one to incorporate into a single quantum description additional degrees of freedom as a subsystem, for example a heat bath or a detector in a laboratory. The formalism contains no fundamental obstacle to the description of an arbitrary compound of physical microsystems. Thus it is tempting to think even of the universe as a whole in terms of quantum theory [1]. Of course, nobody can explicitly specify a quantum state of the universe [2]. Nevertheless, assuming its existence in principle is enough to construct theoretical models of a quantum universe and to study their predictions, at least at a formal level. Demanding research programs, such as quantum gravity and quantum cosmology [3–5], partially rest on this idea.

In spite of these efforts, in this article we will demonstrate that the very concept of a “quantum state of the universe” is doomed to failure. While this conclusion is not entirely new [6], we feel that it has not received the attention it deserves. Indeed, publications employing a quantum state of the universe, in whatever specification, continue to appear. Therefore, our goal here is to reconsider this concept and clearly present arguments decisive for its rejection. In this way we also declare our position in the recently revived debate on the meaning of quantum theory.

The logical structure of our reasoning is as follows. Taking (U), (F) and (MI) for granted, it follows that (QU) is excluded. Here (U) stands for a definition of the concept of “universe”, (F) for the principle that the interpretation of any physical theory has to rely on facts, (MI) for a minimal interpretation of quantum theory, and (QU) for the claim that there is a quantum state of the universe. Those who tend to escape our conclusion have to decide which of our assumptions they regard as closest to dispensable.

The article is organized as follows. In section II we specify explicitly (U), (F) and (MI). Section III contains our reasoning against (QU). In the last section, we discuss and refute possible objections in an interplay of questions and answers.

II. PREREQUISITES

We start with the specification of (U), which defines the most extended object of physical description.

(U) Definition of the Universe. The (physical) universe is the union of all objects and phenomena which are empirically accessible in principle.

Two explanations are in order.
1. An object or phenomenon is *empirically accessible* only if it is intersubjectively perceptible and communicable. Here it is irrelevant whether a living being is actually observing the object or phenomenon. All that matters is that an observation is possible at any time. Empirical accessibility may well require sophisticated experimental manipulations or technical means for observation.

2. “*In principle*” means “supposing perfect measurement apparatuses”. What is to be considered as empirically accessible in principle does not depend on the current state of measurement-device technique. In this sense, cosmic background radiation was “empirically accessible in principle” already in antiquity. In contrast, if quantum theory is true, simultaneous values of mutually incompatible observables are not empirically accessible in principle.

To give some motivation for the principle (F), we first recall the purpose of interpretations of physical theories in general. The goal of an interpretation is a unique relation between the mathematical formalism of the theory and the objects and phenomena which are to be described. Roughly speaking, an interpretation of a physical theory is a set of mapping principles relating certain elements of the mathematical formalism to certain elements of physical reality. If one knows the objects and phenomena to be described, the interpretation shows how to apply the formalism. Vice versa, if one knows the formalism, the interpretation shows which objects and phenomena the theory is able to describe.

(F) **Principle of Relation to Facts.** Every interpretation of a physical theory has to relate certain elements of the mathematical formalism of the theory to *conceivable facts*.

Some explanations are in order.

1. Here a *fact* is only what is empirically accessible in principle in a single measurement on an individual system.

2. *Conceivable* facts are facts that *may* but need not exist in reality, supposing the theory is exactly valid. They are the kind of facts considered in thought experiments. We note that in some situations it is empirically clear that they do not exist in reality, as is the case in counterfactual reasoning.

3. The purpose of the concept of *conceivable* facts is not to test the empirical adequacy of the theory (for that the *real* facts are decisive), but only to specify the testible statements of the theory. Strictly speaking, the theory can only be tested empirically when its interpretation has been specified by means of conceivable facts. In this sense, interpretation is a precondition of testability.

4. Principle (F) excludes an understanding of “interpretation” in the broad sense of attributing “meaning” to a theoretical concept by means of free human imagination regardless of any empirical relevance. Speculative imagination in physics, useful as it is for the invention of new hypotheses, has to pay tribute to the methodological basis of theoretical concepts, which is epitomized in principle (F).

Examples of conceivable facts are the values of all observables in classical mechanics. A probability density on phase space is not a conceivable fact, since it incorporates some ignorance about the classical system under consideration. However, the point in phase space that describes the “real” state of the system represents a conceivable fact, even if it is not precisely known (which is the typical situation in classical statistical mechanics).

In quantum theory, all internal parameters that characterize a quantum system (such as mass, spin, charge etc.) stand for conceivable facts. In contrast, a value of a quantum observable (such as position, energy, orbital angular momentum etc.) is never assigned as a fact to a system in all of its states that show quantum uncertainty for this observable, namely in its non-eigenstates. Also, it is not a conceivable fact that a certain Schrödinger wave function (in other words, pure state) is given, since this function cannot be tested by a single measurement on an individual system. Hidden variables would be connected with conceivable facts (hence the efforts to introduce them), but they are not part of the quantum formalism. In any case, results of measurements performed on an individual quantum system are always conceivable facts.

Our third premise is the set of basic rules of how to apply quantum theory. These rules are almost uncontroversial among the proponents of different quantum interpretations.
**MINIMAL INTERPRETATION OF QUANTUM THEORY.** Every state of a given quantum system yields probabilistic predictions for all observables that can be measured on this system. More precisely, let the quantum state \( W \) be represented by a positive trace-one operator \( W \) acting on some complex separable Hilbert space \( \mathcal{H} \), and the observable \( \mathcal{A} \) by a positive-operator-valued measure \( E_{\mathcal{A}} \) on a suitable set \( \Omega \) with measurable subsets \( X \subseteq \Omega \). Then the trace \( \text{Tr}[W E_{\mathcal{A}}(X)] \) is the *probability* of finding a result in \( X \) when \( \mathcal{A} \) is measured on the system in the state \( W \).

Some comments apply.

1. Remarkably, the possible outcomes of measurements in the sense of experimental physics are related to the notions “measure” and “measurable subset” in the sense of mathematical measure theory (see, for example [1]). The real line \( \mathbb{R} \) or suitable subsets of \( \mathbb{R} \) are typical examples of the set \( \Omega \) of the possible values of \( \mathcal{A} \).

2. The class of quantum observables represented by positive-operator-valued measures extends the more familiar class of observables represented by self-adjoint operators in a substantial way [2]. In the special case that \( \mathcal{A} \) is represented by a self-adjoint operator \( A \) on \( \mathcal{H} \), the operator \( E_{\mathcal{A}}(X) \) is simply given by the spectral projection of \( A \) associated with \( X \subseteq \Omega \subseteq \mathbb{R} \), in symbols, \( E_{\mathcal{A}}(X) = I_X(A) \). Here \( I_X \) is the indicator function of the set \( X \).

3. The essence of (MI) does not depend on the formal frame in which quantum theory is formulated. Observables and states may be represented, as above, by operators on a Hilbert space, or they may, more abstractly, be postulated as elements of a suitable algebra and as positive linear functionals on this algebra, respectively. The choice of a specific mathematical axiomatization is irrelevant to the subsequent reasoning.

4. (MI) does not ascribe a value of \( \mathcal{A} \) to the quantum system before \( \mathcal{A} \) was measured, not even in the simple case that \( \mathcal{A} \) is represented by a self-adjoint operator with a purely discrete spectrum. After each single measurement, however, a measurement result must be assigned to the individual system as a fact. The relative frequency of the occurrence of such facts in suitable experiments is just what the probability \( \text{Tr}[W E_{\mathcal{A}}(X)] \) predicts. Indeed, the only way to interpret probabilities in physics is to compare them with relative frequencies, that is, to interpret them statistically. Details are given in the next section.

**III. REASONING**

Our reasoning against a quantum state of the universe goes as follows. For the physical interpretation of a quantum state in accordance with (F) and (MI), it has to be conceivable in principle to produce an (infinite) collection of measurement results as facts for every observable, to “read them off” and to determine their relative frequencies. The interpretation of the quantum probability prediction about the observable \( \mathcal{A} \) in state \( W \) then implies equating the probability \( \text{Tr}[W E_{\mathcal{A}}(X)] \) with the relative frequency of measurement results in \( X \), for all \( X \subseteq \Omega \). Actually, the empirical significance of \( W \) can be illustrated completely by the histograms of such collections of results for all observables that are conceivably being measured in the state \( W \).

Every single measurement of an observable \( \mathcal{A} \) on any quantum system produces just one fact. For the empirical significance of the quantum state \( W \) it is irrelevant, whether different quantum systems of the same type are prepared at the same time into the state \( W \), or the same quantum system is repeatedly prepared into the state \( W \) at different times. In either case, an ensemble of identically prepared quantum systems leads in the end to a collection of facts with the same histogram. It is this collection of facts given after the measurements that serves to interpret the corresponding probability prediction and, thereby, the quantum state. (MI) obeys (F) exactly in this way.

In order to consider the physical universe as a genuine quantum system, one either had to prepare it arbitrarily often into the same state, or one had to prepare arbitrarily many universes of the same type into the same state. In both cases, it is inconceivable in principle to register relative frequencies of facts after measurement, supposing the total information about the universe is encoded in its state.

In the first case, the universe cannot remain in the same state as before a measurement and, at the same time, exhibit the result of this measurement. In the second case, “reading off” relative frequencies contradicts (U): A universe consisting of all physical objects and phenomena by definition, cannot be compared with additional facts from “parallel universes”, that is, from “outside”.

Consequently, a collection of measurement results (in the sense explained above) for the system “universe” cannot consistently be conceived of. Therefore the concept “quantum state of the universe” is lacking a sound physical
interpretation, taken for granted (F) and (MI). Roughly speaking, any proposal to provide this concept with empirical significance is ruled out by the probabilistic character of quantum theory. It is not enough to refute merely the more bizarre proposals (such as splitting the apparatus [10]). There is no way to appeal to a “quantum state of the universe” within the methodological principles of physics.

We state some obvious but far-reaching consequences of this conclusion:

1. There has never been a “quantum state of the universe” in the past. The origin of the physical universe cannot be explained from a quantum state alone, neither by amplitudes to appear from nothing nor by a hypothetical tunnelling phenomenon [11]. This conclusion does not depend on whether the universe is open or closed, inflationary or not. There is no exclusively quantum-theoretical cosmogenesis on principle.

2. The physical universe as a whole is not subjected to a purely quantum-theoretical dynamics as was proposed in [12]. In this sense, there is no strict quantum cosmology [13].

3. A “theory of everything” which aims at a description of all physical systems and their interactions cannot rely exclusively upon quantum-theoretical basic concepts. There is no quantum theory of gravity with an interpretation which allows for a “quantum state of the universe”.

IV. DISCUSSION

The reasoning presented in the last section may give rise to a number of interesting questions, which we are going to discuss now. In doing so, we want to anticipate and refute possible objections.

Question 1: If the need for empirical accessibility is taken seriously, then some kind of experimental arrangement, shortly called “apparatus” in the following, is indispensable. Does not every physical description of the universe necessarily comprise as part of the universe the apparatuses suitable to test this description? Isn’t this problem even more fundamental than how to apply quantum theory to the universe as a whole? Isn’t a classical state of the universe inconceivable as well?

Answer 1: We abstract from all concrete measurement methods. We push idealization even thus far as to neglect the material configuration of the apparatus completely. In this vein, one can relate a physical description to something empirically accessible in principle without explicitly paying attention to internal states of the apparatus or to reactions of the apparatus to the system of interest. This stage of idealization is well suited to find out which picture, or better caricature, of physical reality a theory permits. Thus, a classical pure state of the universe is conceivable (and has indeed been conceived, as is well known, in the 19th century in the guise of the Laplacian demon). Our reasoning against a quantum state of the universe notably holds true for every probability prediction about the physical universe, be it of quantum origin or not. Consequently, there is also no classical mixed state of the universe, whence cosmology cannot rely on probability densities on phase space.

Question 2: In contrast to classical physics, in quantum theory state transformations caused by apparatuses play a central role. How can one then justify to establish quantum descriptions without explicitly incorporating preparation and measurement apparatuses?

Answer 2: All you need is (F). In order to interpret probability predictions physically, it is indispensable to consider collections of conceivable measurement results as facts. Usually these facts are read off the apparatuses, but every description of apparatuses going beyond the facts themselves may fall victim to our idealization.

Question 3: Collections of measurement results can only be thought of as produced by repeated preparation and measurement. Isn’t it, in view of such an ensemble interpretation [15], always (and not only for the universe as defined by (U)) impossible to assign a quantum state to an individual system?

Answer 3: Whether or not a certain quantum state is given cannot be tested empirically in a single measurement on an individual system. It is, however, not a priori meaningless to assign a certain quantum state to an individual system, as long as one knows the preparation apparatus (whose state is, notably, not part of the quantum description). If it is a legitimate thought experiment to check at an infinite ensemble into which quantum state a specific apparatus prepares, then it is also legitimate to ascribe this state to each and every individual system prepared by this apparatus. There is no fundamental problem with this for microsystems, but there is one for the universe.

Question 4: The idealization relevant for interpretation extends so far as to make irrelevant the material configuration of apparatuses (Answer 1), as well as to legitimize thought experiments with infinite ensembles of quantum systems (Answer 3). Why is it then forbidden to imagine an infinite multitude of identically prepared quantum universes? Why should different facts exist in different “parallel universes”?

Answer 4: Abstraction and idealization in physics lead only to simplified descriptions of what is empirically accessible in principle. Because any view from outside the universe is inconceivable by the definition (U), a
multitude of universes or a comparison between different universes remains forbidden, even if idealization is pushed to the extreme. It is legitimate to imagine an infinite ensemble of electrons, only because it is conceivable in principle to prepare many electrons (or one electron repeatedly) into the same state. For the universe, the situation is fundamentally different. Even if the material configuration of apparatuses is completely neglected, there remains a difference in their logical status: An apparatus for the observation of an electron is surely outside the electron, but an apparatus for the observation of the universe is surely not outside the universe.

**Question 5:** The real structure of nature does not depend on definitions. Answer 4, however, seems to do so. Why are cosmological scenarios excluded which involve a multitude of universes, each being part of nature? “Universe” means “all embracing”, but why should a physical universe as an object of cosmology be literally everything?

**Answer 5:** One can, of course, give up (U) and use the word “universe” in a less embracing sense. But then, our reasoning and conclusion remain valid for what was originally meant by (U).

**Question 6:** Real apparatuses consist of atoms, and atoms are undisputedly quantum systems. Why can one then rely on facts to interpret quantum states without describing the emergence of these facts within the conceptual frame of quantum theory? Doesn’t the whole reasoning rest on an artificial opposition between quantum predictions and classical apparatuses due to over-idealization, and hence lack physical relevance?

**Answer 6:** Indeed, the application of (MI) presupposes that a collection of facts comes out of every sequence of measurements. (MI) gives no hints on how these facts come into existence or on how their emergence could be described theoretically. This notorious “quantum measurement problem” cannot be solved or avoided by explicitly taking into account the apparatus and the environment as quantum systems. In particular, purely quantum-dynamical theories of decoherence do not explain the emergence of facts in single measurements, not even for all practical purposes. The idealization chosen here favours the sudden emergence of a definite fact in a spontaneous quantum event once a measurement is carried out on a quantum system. From then on the fact persists. Conventional quantum theory expresses such an individual quantum event as a suitable state collapse. Encouraged by these facts and in the tradition of Niels Bohr, we insist that the classical description of apparatuses is a necessary independent input to every quantum description. By “classical” we do not refer to the laws of classical physics, but only to the applicability of classical logic to the facts presupposed by (MI). The relevance of these facts to interpretation is a direct consequence of (F).

**Question 7:** The unsatisfactory special role of the apparatuses and the desire for a description of the universe as a closed quantum system have been two essential motivations for the development of the formalism of consistent quantum histories. Hasn’t the state concept lost its fundamental status in this modification of the quantum formalism, so that the reasoning presented above has become obsolete?

**Answer 7:** Quantum probability goes without histories, mathematically and physically. The formalism of consistent quantum histories is burdened with a fundamental freedom of choice of a consistent family or a framework. Among the various imaginable quantum histories, there is no unique procedure to discriminate in a given physical situation between facts and non-facts. In the histories formalism it is not unambiguously expressible that one observable has an actual value due to the real experimental setup, while another (incompatible) one has not. This is the ultimate reason why the histories approach has been criticized repeatedly. Independently of its applicability to the universe, the quantum-histories approach thus fails to satisfy principle (F). For this reason it lacks a sound physical interpretation. This is fatal to the whole approach, but it is far from being acknowledged by its adherents.

Finally, one could ask how to do cosmology at all in the era of quantum theory. We stress that this problem appears to be puzzling only through the dogma of the universal applicability of quantum theory. In accordance with Ludwig and others, we suggest to drop this dogma. In the same way as the description of a quantum-mechanical microsystem requires classical apparatuses as a fundamental concept, facts could come into play in the description of the early universe and within grand-unification programs, as a fundamental concept apart from quantum uncertainty. We think that this dichotomy is unavoidable. Moreover, it is by no means evident that all physical systems must possess quantum states.

In conclusion, we have shown that the universe as a whole cannot be ascribed a quantum state with a sound interpretation, irrespectively of specific cosmological models. Thus, it makes no sense to postulate such a state hypothetically and treat it like a very complicated quantity, about which one doesn’t yet know enough. This conclusion should serve as an interpretational boundary condition for working out cosmological theories. Its enforcing character is based on conceptual and methodological rigor. This is a step beyond Occam’s razor, which has so often been the main tool of heuristic argumentation against a multitude of universes: While the razor cuts off only what is physically legitimate but redundant, the idea of an ensemble of universes is at best metaphysical.
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