The assumption of a perfectly measurable space-time, the measurement problem in quantum mechanics and the nature of physical laws

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Abstract

The history of physics shows us that even when we have the correct physical theories in our hands, it takes time to realize their most profound implications. In many occasions this is because theories that imply a new paradigm in physics are initially formulated in terms of quantities and assumptions that predate the paradigm. This obscures the true meaning of the theory in question. An example is Maxwell's electromagnetism: it is a Lorentz-invariant theory but such feature was not noticed by Maxwell, since he cast it in terms of non-invariant concepts. We argue that we face a similar situation in quantum mechanics. The theory is ordinarily formulated in terms of a classical background space and time that one assumes can be measured with infinite precision. When one takes into account that space and time have to be described as quantum entities, with fundamental limitations in their measurement, apparent conceptual problems in the quantum theory, as the measurement problem, disappear. One ends up with a quantum mechanics that is complete and does not require an external classical reality for its existence. A complete quantum theory in turn leads us to revise long held assumptions about the nature of physical laws. It naturally takes us to the position emphasized by regularist philosophers for years: physical laws derive their truth from actual relations within the world, they express only what *does* occur. They refer to the effects that some systems may have on others and not to what *must* occur in absolute, non-relational ways. Due to the probabilistic nature of the theory another assumption to be revised concerns the "closure" of physics: the laws of physics do not dictate everything that happens in the natural world. In turn this may have implications in many other philosophical issues, like for instance, the mind/body problem.

I. INTRODUCTION

Examining the history of physical ideas, one notices that new theories tend to get (at least initially) formulated in terms of concepts and assumptions that are natural in theories that preceded them, but that may actually obscure the interpretation of the new theory being introduced. A paradigmatic example is given by Maxwell's theory, which is invariant under Lorentz transformations, and therefore compatible with special relativity. Maxwell, however, never knew it. He had formulated the theory in terms of three dimensional vectorial calculus and in such a language it is not easy to see that the theory is Lorentz-invariant. On the other hand, formulating it in terms of four-vectors makes the invariance immediately apparent. Another example is general relativity. The theory is formulated in terms of space-time coordinates, as if one were given a background space-time. But the theory is background independent, or in other words, invariant under general coordinate transformations.

These questions about preconceptions are not just conceptual theoretical issues that can be brushed away from a practical point of view. They can often lead to serious problems in the interpretation of the theories being considered. In the case of general relativity, for example, a tendency to work with specific coordinate systems obscured the concept of black hole for almost fifty years. The Schwarzschild solution was obtained in closed form in 1916, yet its proper interpretation was only achieved in the 1960's when Kruskal and Szekeres truly revealed the geometrical meaning of the solution. Some the most brilliant physicists of the 20th century were confused by this problem and many of them, including Einstein, passed away without ever knowing its solution. Many of them made significantly incorrect statements about the nature of the solution that today we would not tolerate from graduate students taking a course in general relativity.

We would like to argue that a similar situation has arisen in quantum mechanics, leading to the "measurement problem" of the theory. Quantum mechanics is typically formulated in terms of a classical space-time. Wavefunctions are functions of time (and in quantum field theory also of space). Time (and space) are assumed to be continuous variables that can be determined with arbitrary precision. This would be appropriate if one has a background space-time on top of which the quantum theory is built. And indeed, most common treatments actually assume this. But ultimately the quantum theory should be made compatible with the physics we know to be true. And the latter is given, among other things, by general relativity (or a suitable generalization like string theory), which are known or expected to be background independent theories. No space-time is given a priori. One can construct one using observable quantities ("clocks and rulers") but the latter are ruled by the laws of physics, including gravity and quantum mechanics. And those rules impose fundamental limitations on their measurement, in particular on the accuracy with which one can measure them. Several authors have tried to estimate the ultimate accuracy that the laws of gravity and the quantum theory impose on the measurement of space-time [1]. We do not need to concern ourselves too much with the details of these estimates, just to know that suitable estimates exist, and that they imply that the errors in measurement of times (and distances) grow as some (perhaps fractional) power of the quantity being measured. This is quite a reasonable assumption. We will see that this shift in assumption, i.e. that space-time cannot be measured with arbitrary precision, actually helps make the theory more consistent in a way that has deep implications for the notion of physical laws.

II. THE MEASUREMENT PROBLEM IN QUANTUM MECHANICS

In traditional formulations of quantum mechanics it is claimed that the state evolves unitarily through Schrödinger's equation, except when a measurement takes place. In that process the state is supposed to change violently into a statistical mixture. The fact that the theory somehow has two different evolutions that are incompatible with each other is the crux of the measurement problem.

A potential answer to the problem is given by *decoherence*. When a measurement is performed on a quantum system, the latter interacts with a measurement device and an environment, consisting of a large number of degrees of freedom[1]. For a system isolated from others, the complete system consisting of the system plus environment plus measuring device evolves unitarily all the time. However, due to the large number of degrees of freedom of the environment, its interaction with the system makes the quantum state of the latter resemble that of a statistical mixture. And in fact, due to the large number of degrees of freedom that a typical environment offers, the resemblance of the state of the system to a statistical mixture is very close. This has led people to claim that "for all practical purposes"

[1] More generally, instead of speaking of measurements, one speaks of "events" to refer to an interaction of the system with an environment, not necessarily involving a measuring device.

decoherence solves the measurement problem.

But a solution "for all practical purposes" is not a conceptual solution. For instance, one could wait for a long time after the interaction with the environment and the quantum coherence in the wavefunction of the system could reappear, phenomena known as "revivals". For most systems interacting with a macroscopic environment the typical time one would have to wait would probably exceed the age of the universe. But that does not mean that at a conceptual level the problem is solved: from a purely logical standpoint the theory is still inconsistent.

III. FUNDAMENTAL LIMITATIONS AS A CONCEPTUAL ADVANTAGE

The problems detailed in the previous section all stem from the fact that one assumes that although the state of the system after a measurement is close to that of a statistical mixture, it is not, and, in particular, one could actually somehow tell the difference. The example mentioned of "waiting for a long time" could be a way. Another way could be to make measurements on the total system, including the environment, that give different results in the state considered than in a statistical mixture, as suggested by d'Espagnat [2].

We would like to argue that such measurements, which could reveal the state is not in a pure statistical mixture, are not allowed due to the fundamental limitations in the measurement of times and distance that a background independent theory of gravity imposes on the quantum theory. The easiest way to see this is to consider the example of "waiting for a long time" to see a revival of quantum coherence. When quantum mechanics is formulated in terms of real clocks that have inaccuracies its evolution stops being unitary [3]. Although the underlying theory is unitary, our clocks are not accurate enough to keep track of such unitarity. As a consequence "waiting for a long time" does not help to see quantum coherence revive. Quite on the contrary, due to the loss of unitarity as time evolves one sees the chance of quantum coherence reemerging diminishes.

We have probed in some detail other strategies that have been proposed in the literature to notice that the state is not a purely statistical mixture and shown that the loss of coherence inherent to the use of real clocks and rods prevents from determining that the state is not in a purely statistical mixture [4].

The measurement problem is therefore solved by decoherence not "for all practical purposes" but at a fundamental level when one accepts the fundamental limitations on the measurement of space-time that are imposed by modern background independent theories of gravity.

IV. A COMPLETE QUANTUM THEORY

Having a quantum theory where the measurement problem is solved in the proposed way has other satisfactory conceptual implications. We now have an objective, observer independent, criterion for determining when an event has taken place. When a quantum system, through its interactions (with the environment, other systems and/or measurement devices) acquires a quantum state that is indistinguishable from a pure statistical mixture, an event has taken place. What does indistinguishable in this context mean? Consider all possible physical predictions that could be made about the physical system, and the limitations imposed on their measurement by assuming that one is working in a background independent context. If they cannot distinguish between the state and a statistical mixture we say that an event has taken place. Notice that for this definition of event no observer or measuring apparatus are needed. Events occur all the time when quantum systems interact, irrespective of the presence of an observer: the definition is objective.

This allows us to build a reality out of the quantum theory itself and provides an ontological basis to make the quantum theory complete. We therefore have an interpretation of quantum mechanics, which we have dubbed *The Montevideo Interpretation* [5]. The resulting picture is one of events that does not require the existence of a classical world for its definition. Events occur as a result of free random choices of the systems. Such choices must be compatible with the probabilities implied by the evolution of the wavefunction of the system described in terms of real quantum clocks. This evolution is unique, one does not assume to have a separate behavior when events take place. Notice that there is no deterministic prescription for the outcome of a measurement process or production of events. The criterion of indistinguishability only determines when events may occur, it does not determine which specific event will occur. This has implications for the nature of physical laws.

V. THE NATURE OF PHYSICAL LAWS AND THE MIND/BODY PROBLEM

The above proposal suggests a revision of the assumptions underlying the concept of natural law. It does so in two senses:

First, it makes evident something that *regularist* philosophers have emphasized for years (e.g. [6]): physical laws derive their truth from the actual connections within the world; they express only what *does* occur. Ernest Nagel in "The Structure of Science" [7] describes this position in the following terms: "Hume proposed an analysis of causal statements in terms of constant conjunctions and de facto uniformities... According to Hume [physical laws consists] in certain habits of expectation that have been developed as a consequence of the uniform but de facto conjunctions of [properties]." In other words, they refer to the effects that some systems may have on others and not to what *must* occur in absolute non relational ways. The alternative position to the regularist is "necessitarianism" (e.g. [8]), which states that laws of nature are *principles* which govern the natural phenomena, that is, the world *necessarily obeys* the laws of nature. The laws are the cornerstone of the physical world and nothing exists without a law. The existence of the undecidability we pointed out strongly suggests that the *regularist* point of view is more satisfactory since what matters in this case is having a state being distinguishable from others by its physical effects. That is, we are separating here the intrinsic nature of the system, which is not relevant for the identification of physical laws, and its behavior with respect to other systems which provides the indistinguishability criterion that determines when events occur.

A second assumption this point of view leads us to revise is that physical laws do not dictate entirely the behaviors of nature. In fact, we have observed that there is no deterministic prescription for the outcome of a measurement process or any production of events. The criterion of indistinguishability only determines *when* events may occur. It does not determine which specific event will occur. This property is related with the issue of the "closure" of physical laws. Nancy Cartwright has defined closure as follows: "Are there (in God's great book of Nature) laws of physics that dictate everything that happens in the natural world? Or, more narrowly, everything that happens in the physical world?" The existence of random choices at events among the possible outcomes resulting from the statistical mixture suggests a negative answer to this question. The laws of physics only specify probabilities for this.

The necessitarian point of view was originally attributed to the “hand of God” who would have imposed physical laws on nature in much the same way as He imposed moral laws on human beings. Even though this theistic account has been abandoned in the twentieth century, widely held current views on laws of nature preserve the older prescriptive tone. For the regularist, physical laws are simply descriptions of the world's regularities. Regularism is tightly related to the thesis that physics is not closed, but a description of the regularities of a richer reality.

Adopting the point of view about the natural laws and their closure suggested by the Montevideo interpretation of quantum mechanics could also open new perspectives about many other philosophical problems, for instance the mind/body problem. The key point behind the conscious experiences of any living organism, is that “there is something it is like to be in that organism” as is claimed by Ernest Nagel in his famous article “What it is like to be a bat” [9]. There are unique and non transferable experiences that each of us have, there are qualitative feelings, also known as *phenomenal qualities or simply qualia* [10]. This property of the mental entities has been the hardest one to reconcile with the usual (“closed”) views on the laws of physics since it is not accessible empirically. Already Socrates, in his dialogue with Theaetetus when answering a question by the latter about “what is color?” says that the color is “peculiar of each percipient” and he asks the young student “are you quite certain that the several colors appear to a dog or any animal as they appear to you?” Theaetetus responded negatively, to which Socrates adds: “or that anything appears the same to you as to another man?” This eminently private and subjective aspect is part of the conscious experience. Since the regularist point of view that emerges from the Montevideo interpretation and its ontology of states and events does not imply a closed nature for the laws of physics, it naturally accommodates aspects not accessible empirically.

In fact, it has been noted some time ago by philosophers that an ontology of states and events allows a promising approach to the problem of consciousness. The position known as *neutral monism* holds basically that events can be associated both to physical and phenomenal aspects. It is a particular case of the double aspect theories in which one class of entities has both physical or third person manifestations and psychological or first person manifestations not accessible empirically. That is, each event is something for itself and something for other events. Neutral monism can be attributed to Mach [11], but it has illustrious predecessors that held, like Spinoza [12], that the physical and the mental are two aspects of the same substance. Throughout his life Bertrand Russell adopted different positions close to neutral monism. For instance in [13] he said “Matter in a given place are all the events that are there...” and he goes on to say in the same book that such vision of matter implies that we “do not have to deal anymore with what used to be mysterious about the causal theory of perception: how a series of waves of light or sound produce an event apparently totally different from them in its character.” That is, they produce sensations.

Inspired by the necessitarian point of view, Honderich [14] has postulated a *law* of correspondence between the two aspects, the neuro-physiological (neural) and the phenomenal. This appears unsustainable when one of the aspects, the phenomenal, does not allow a third person access and therefore cannot be subject to empirical laws, making impossible to objectively compare the phenomenal properties that occur in each case.

Instead of postulating the existence of laws not accessible to the experience, a regularist point of view, where the closure of the physical laws are not assumed, allows a conception in which one only needs to assume that the physical entities, states and events present both aspects that have an ontological connection. Of them only one, the neuro-physiological aspect, admits a physical description. This provides a richer and deeper view of mental phenomena and allows to overcome the epiphenomenalist challenge that reduces consciousness to a “mere subproduct of the bodily behavior, lacking in all capacity to modify that behavior, the same way that the sound of the steam siren accompanies the working of a steam engine... [although] it lacks any influence on its machinery” [15].

VI. SUMMARY

We have argued that the measurement problem in quantum mechanics arises because one is insisting in framing the theory in terms of a predefined classical background space-time. When one takes into account that modern theories of gravity are background independent and that space-time has to be reconstructed from observable quantities, fundamental limitations in the measurements of space and time appear. As a consequence of them decoherence provides a fundamental (and not just “for all practical purposes”) solution to the measurement problem. Events occur when the quantum state of the system becomes indistinguishable from a statistical mixture for all possible physical predictions taking into account limitations in their measurement. The resulting quantum theory is a theory of events that can be constructed without reference to an external predefined classical world. It opens new perspectives on the notion of physical law, suggesting a regularist vision of reality which in turn can open new possibilities to understand deep issues like the mind/body problem.

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