1-1-2008

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Rodolfo Gambini
Universidad de la Republica

Jorge Pullin
Louisiana State University

Recommended Citation

Gambini, R., & Pullin, J. (2008). Quantum cosmic censor: Gravitation makes reality undecidable. *International Journal of Modern Physics D, 17* (13-14), 2535-2538. https://doi.org/10.1142/s0218271808014047

Quantum cosmic censor: gravitation makes reality undecidable

Rodolfo Gambini
Instituto de Física, Facultad de Ciencias,
Universidad de la República, Iguá 4225,
CP 11400 Montevideo, Uruguay
rgambini@fisica.edu.uy

Jorge Pullin
Department of Physics and Astronomy,
Louisiana State University,
Baton Rouge, LA 70803-4001
pullin@lsu.edu

(Dated: March 11th 2008)

When one takes into account gravitation, the measurement of space and time cannot be carried out with infinite accuracy. When quantum mechanics is reformulated taking into account this lack of accuracy, the resolution of the measurement problem can be implemented via decoherence without the usual pitfalls. The resulting theory has the same physical predictions of quantum mechanics with a reduction postulate, but is radically different, with the quantum states evolving unitarily in terms of the underlying variables. Gravitation therefore makes this worrisome situation, potentially leading to two completely different views of reality, irrelevant from an empirical point of view. It may however be highly relevant from a philosophical point of view.

This essay links together the findings of several recent papers by the authors (see [1] for a pedagogical review). These papers draw upon the following well known observations. First of all, it is well known that in quantum mechanics one needs to expend energy in order to achieve accurate measurements [2]. On the other hand, gravity puts fundamental limits on how much energy can be concentrated in a measuring device before it turns into a black hole. Coupling together these two observations, one concludes that there exist fundamental limits, imposed by quantum mechanics and gravity, on how accurately we can measure distances and time [3, 4].

On the other hand, quantum mechanics is usually formulated on a space-time manifold that one assumes can be measured with arbitrary accuracy. Acknowledging that real clocks and rods that one may use to measure space-time are not arbitrarily accurate requires reformulating the theory in terms of such clocks and rods [1]. It is not too surprising that in the resulting picture one does not have a unitary evolution: although the underlying theory is unitary, our clocks and rods are not accurate enough to give a depiction of evolution that appears unitary. A detailed calculation shows that quantum states described in terms of a realistic clock variable T lose coherence as,

$$\rho(T)_{nm} = \rho(0)_{nm} \exp\left(i\omega_{nm}T\right)\left(-T_{\rm Planck}^{4/3}T^{2/3}\omega_{nm}^2\right) \tag{1}$$

where $\rho(T)_{nm}$ is the density matrix element in an energy pointer eigenbasis, ω_{nm} is the Bohr frequency associated with states n and m in the basis and $T_{\rm Planck} \sim 10^{-44}s$ is Planck's time. The effect is too small to be observed with current technologies, but might be within the reach of technologies of the relatively near future [5].

Although experimentally not interesting today, this effect has important conceptual implications, in particular for the *measurement problem in quantum mechanics* . The latter refers to the fact that the system being measured abruptly falls into an eigenstate right after a measurement has been performed. This is usually referred to as the reduction process. The conceptual problem is: how can one explain this abrupt change of state? One possible explanation is by saying that there exists an interaction between the system being measured and the environment. This interaction selects a preferred basis, i.e., a particular set of quasi-classical states that commute with the Hamiltonian governing that interaction. Decoherence quickly damps superpositions between the preferred states when only the system is considered (i.e., when the environment is neglected), and only classical, well-defined properties appear left to an observer.

The above explanation of the measurement problem encounters some difficulties. Although we cannot do justice to the full extent of the problem and its associated vast literature in the confines of this essay, our claim is that the fact that pure states evolve naturally into mixed states contributes to surmounting at least some of those obstacles [6]. The usual Hamiltonians describing the interaction between the system and the environment lead to off diagonal terms in the density matrix that are oscillatory functions of time. Typical environments contain a much larger number of degrees of freedom than the systems being measured. Therefore the common period of oscillation for the off diagonal terms to recover nonvanishing values is very large, often larger than the age of the universe. In practical terms, the off diagonal elements of the density matrix can be considered to be zero. But conceptually, there is the remote possibility that quantum coherence would "revive". The fundamental loss of coherence due to our inability to measure space-time has the attractive feature of killing off the possibility of "revivals" in a fundamental, inescapable way. If one attempted to "wait longer" to see the effects of revivals, the effect we introduce just becomes larger. Therefore off-diagonal terms will never see their initial values restored, no matter how long one waits. Other ways of distinguishing between a unitary evolution and the state reduction, as the ones proposed by d'Espagnat ([7] p. 181) do not appear possible to be realized due to this process either. We therefore claim that quantum mechanics formulated with real clocks and rods can, thanks to fundamental decoherence, does not need a reduction postulate.

This leads us to the main point of the essay: undecidability. One cannot decide whether the physical world does in fact contain reduction of quantum states or not. In fact, it could even be conceivable that sometimes there might be reduction, sometimes not, and we do not have reasons to expect one or the other in a given instance. There is no way to tell between usual quantum mechanics with a reduction process, on the one hand, and quantum mechanics with real clocks and decoherence instead of the reduction process. The difference between these two views of nature is enormous. In one of them quantum states are given "once and for all" as initial conditions. The evolution is unitary, and what we perceive as loss of unitarity is due to our inability to access the underlying variables of the theory, due to gravitational limitations. In the other view, quantum states are continually evolving due to reduction processes.

In philosophy there are different attitudes that have been taken towards the physical laws of nature (see for instance [8]). One of them is the "regularity theory"; in it, the laws of physics are statements about uniformities or regularities of the world and therefore are just "convenient descriptions" of the world. The laws of physics are dictated by a preexisting world and are a representation of our ability to describe the world. Another point of view is the "necessitarian theory", which states that laws of nature are "principles" which govern the natural phenomena, that is, the world "obeys" the laws of nature. The laws are the cornerstone of the physical world and nothing exists without a law. The presence of the undecidability we point out suggests strongly that the "regularity theory" point of view is more satisfactory.

If one takes seriously the regularity point of view one can ponder about the nature of reality. Does the physical world have a reduction process, does it not, or does it depend on the case? In the case in which there is no reduction process, in the Heisenberg picture the state of a system is given and eternal. If there is a reduction process the state changes every time there is an event resulting in a measurement. The third possibility, which is suggested by the undecidability, is that the system may choose between behaving as if there is a reduction process or not. That is, after the observation of the event either the system simply behaves as if it were part of the universe and its state were that of the universe or if as its state would be given by the reduction postulate. In the first case the system would keep its entanglement with the rest of the universe (i.e. the environment), in the second it will lose its entanglement. This free act of the system will not imply any violation whatsoever of the laws of physics.

If one adopts what is probably the most attractive view that considers that the universe always evolves unitarily and therefore quantum states are determined once and for all no matter what is the chosen behavior of the subsystem under observation one needs to face the problem of when do events happen in such a framework. Our point of view is that an event occurs when the experimental distinction between coexisting or exclusionary alternatives becomes undecidable, since in that instant the predictions of the laws of physics are not altered by the possible reduction of the state of the system associated with the information acquired when the event takes place.

This situation is unusual in physics: there have never been two theories that describe reality in rather starkly different ways and nevertheless have the same experimental predictions. The fact that gravity seems to be cornering us into this situation is perhaps the ultimate expression of a sort of "generalized cosmic censorship" in the sense that there will be aspects of nature, when gravity is taken into account, that we just will not be able to probe. In this case, the basic structure of quantum theory itself!

This work was supported in part by grants nsf-phy0650715, and by funds of the Horace C. Hearne Jr. Institute for Theoretical Physics, FQXi, PEDECIBA (Uruguay) and CCT-LSU.

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