ITP-UU-05/35
SPIN-05/29

DOES GOD PLAY DICE?*

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Summary

Some very persistent problems in our attempts to reconcile the theory of general relativity to quantum mechanics, lead one to suspect that the fundamental principles of both of these theories will have to be reconsidered.

September 27, 2005

*Submitted to *Physics World*, December 2005

If there is any pre-conceived notion concerning the laws of nature, one that we can rely upon without any further questioning, it is the assumption that they are controlled by strict logic. Under all conceivable circumstances, the laws of nature should dictate how the universe evolves. Curiously, the theory of quantum mechanics has given a new twist to this adage: not the precise sequence of events can be predicted, but only statistical averages. *All* statistical averages can be predicted, in principle with infinite accuracy, but nothing more than that.

Albert Einstein was among the first to protest against this impoverishment of the concept of logic. It turned out, however, to be a fact of life. Quantum mechanics is the only known realistic description of the microscopic parts of our universe, and it works just fine. Impoverishment or not, from a logical point of view, quantum mechanics appears to be completely consistent.

The standard model of the fundamental particles is the beautiful outcome of our attempts to combine three basic themes: *quantum mechanics*, Einstein's theory of *special relativity*, and of course the numerous *experimental observations* concerning the subatomic particles. It told us how far we can go with quantum mechanics. Up to arbitrarily small distance- and time scales, nature obeys both quantum mechanics as well as special relativity, provided that we strictly adhere to the principles of *quantum field theory*. It obeys the notions of *locality* and *causality*, and this makes the theory completely comprehensible: our laws are *constructive*, which here means that cause precedes effect, and at tiny time scales, all effects are caused locally.

The standard theory of *general* relativity approaches a similar degree of perfection. Einstein's field equations are also local, and here also, cause precedes effect in a local fashion.

But how to combine the standard model with general relativity? Many theorists appear to think that this is just a technical problem. If I say "Quantum general relativity is not renormalizable", this indeed sounds like just a technicality, but actually, it is much more than that. Renormalizability made the standard model possible, because it allowed us to answer the question: "What happens at extremely tiny distance scales? How do we see that cause precedes effect there?" If this were not the case, we would have no causality or locality, we would have no theory at all.

Asking the same question in quantum gravity does not appear to make sense. At distance scales *small* compared to the Planck scale, some 10^{-33} cm, there seems to be no such thing as a space-time continuum. This is because extreme space-time curvature is no longer prohibited by the gravitational force there. Then what *do* we have at these small distance scales? Are space and time discrete? What then do concepts such as causality and locality mean? Without proper answers to such questions, there is no logically consistent formalism, not even a quantum mechanical one.

I am definitely unhappy with the answers that string theory seems to suggest to us. String theory seems to be telling us to believe in "magic": duality theorems, not properly understood, should allow us to predict amplitudes without proper local or causal structures. In physics, "magic" is synonymous to "deceit"; you rely on magic if you don't understand what it is that is really going on. This should not be accepted.

In thinking about these matters, I reached a conclusion that has not at all yet been adopted by many other researchers: the problem lies with quantum mechanics, possibly with general relativity, or conceivably with both.

Quantum mechanics could well relate to micro-physics the same way thermodynamics relates to molecular physics: it is formally correct, but it may well be possible to devise deterministic laws at the micro scale. Why not? The mathematical nature of quantum mechanics does not forbid this, provided that one carefully eliminates the apparent no-go theorems associated to the Bell inequalities. There are ways to re-define particles and fields such that no blatant contradiction arises. One must assume that *all* macroscopic phenomena, such as particle positions, momenta, spins, and energies, relate to microscopic variables in the same way thermodynamic concepts such as entropy and temperature relate to local, mechanical variables. The outcome of these considerations is that particles and their properties are not, or not entirely, real in the ontological sense. The only realities in this theory are the things that happen at the Planck scale. The things we call particles are chaotic oscillations of these Planckian quantities.

An even more daring proposition is that perhaps also general relativity does not appear in the formalism of the ultimate equations of nature. This journal does not allow me the space to explain in full detail what I have in mind. At the risk of not being understood at all, I'll summarize my explanation. In making the transition from a deterministic theory to a statistical treatment — read: a quantum mechanical one —, one may find that the quantum description develops much more symmetries than the, deeper lying, deterministic one. If, classically, two different states evolve into the same final state, then quantum mechanically they will be indistinguishable. This induces symmetries not present in the initial laws. General coordinate covariance could be just such a symmetry.

Nature provides us with one indication perhaps pointing in this direction: the unnatural, tiny value of the cosmological constant Λ. It indicates that the universe has the propensity of staying flat. Why? No generally invariant theory can explain it. Yet, if an underlying, deterministic description naturally features some preferred flat coordinate frame, the puzzle will cease to perplex us.

The cosmological constant problem has always been a problem of quantum gravity. I am convinced that the small value of Λ cannot be reconciled with the standard paradigms of quantized fields and general relativity. It is obvious that drastic modifications in our ways of thinking, such as the ones hinted at in this text, are required to solve the problems addressed here.

References

[1] G. 't Hooft, *How Does God Play Dice? (Pre-)Determinism at the Planck Scale*, in *Quantum [Un]speakables, From Bell to Quantum Information*, R.A. Bertlmann and A. Zeilinger, eds, ISBN 3-540-42756-2 Springer Verlag, pp 307-316. SPIN-2001/09, ITP-UU-01/15, hep-th/0104219.

[2] G. 't Hooft, *Obstacles on the way towards the Quantization of Space, Time And Matter - and possible resolutions*, *Stud. Hist. Phil. Mod. Phys.*, Vol. **32** No 2, pp. 157-180, 2001, SPIN-2000/20.

[3] G. 't Hooft, *A Confrontation with Infinity*, preceeded by an autobiography, in *Les Prix Nobel 1999*, Norstedts Tryckeri, Stockholm 2000, pp. 51 - 74. Reprinted in: *Nobel Lectures, Including Presentation Speeches and Laureates' Biobraphies*, PHYSICS 1996 - 2000, G. Ekspong, ed., World Scientific, pp. 347 - 370.