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Search for Quantum Gravity

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Summary

A satisfactory theory of quantum gravity may necessitate a drastic modification of our perception of space-time, by giving it a foamy structure at distances comparable to the Planck length. It is argued in this essay that the experimental detection of such structures may be a realistic possibility in the foreseeable future. After a brief review of different theoretical approaches to quantum gravity and the relationships between them, we discuss various possible experimental tests of the quantum nature of space-time. Observations of photons from distant astrophysical sources such as Gamma-Ray Bursters and laboratory experiments on neutral kaon decays may be sensitive to quantum-gravitational effects if they are only minimally suppressed. Experimental limits from the Whipple Observatory and the CPLEAR Collaboration are already probing close to the Planck scale, and significant increases in sensitivity are feasible.

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Almost a century has elapsed since Einstein proposed his General Theory of Relativity, in which the curvature of space encodes the classical gravitational field. Somewhat later, first quantum mechanics and then quantum field theory were formulated. All of these theories have been individually tested with great accuracy. However, a consistent quantum version of gravity still eludes us, and it is often thought that quantum gravity must lie beyond present experimental reach.

Attempts to quantize General Relativity may be fitted into three major categories. One tackles the quantization of the geometry of space and time within the framework of local four-dimensional field theories and (non-trivial) extensions thereof, using a *canonical formalism* such as the loop-gravity approach [1], in which the states of the theory are represented as functions of spin networks, leading to a 'polymer' structure of quantum space-time.

The second major category posits a *foamy structure* of quantum space-time [2]. in which Planck-size topological fluctuations resembling black holes, with microscopic event horizons, appear spontaneously out of the vacuum and subsequently evaporate back into it. The microscopic black-hole horizons are viewed as providing a sort of 'environment' that might induce quantum decoherence of apparently isolated matter systems [3, 4]. These are described by density matrices ρ with 'in' and 'out' states that evolve in a manner reminiscent of the quantum mechanics of open systems [3]:

$$\partial_t \rho = i[\rho, H] + \not{\delta} H \rho \tag{1}$$

where H is the Hamiltonian, and the matrix $\not{\delta} H$, which has a non-commutator structure, represents collectively quantum-gravity effects. In this picture, as in the canonical approach, Lorentz covariance may be lost in the splitting between the matter system and the quantum-gravitational 'environment'. Such a breaking of Lorentz covariance could be considered a property of the quantum-gravitational ground state, and therefore a variety of spontaneous breaking.

The third category includes *string theory* and its non-perturbative D(irichlet)-brane extension [5]. The discovery of new non-local solitonic structures (membranes) in string theory has led to a new interpretation of the quantum space-time: D-branes appear as space-time defects, which give rise to a 'discrete' cellular structure in the space-time manifold, in a spirit reminiscent of the loop-gravity formalism. Multiple D-branes may overlap and interact via the exchanges of open strings with ends attached to the brane surface, yielding a non-commutative geometry of space [6, 7].

Further intriguing possible connections between these apparently disparate approaches to quantum gravity have emerged recently. For example, there are conceptual and possibly observational similarities between a 'weave' state in the loop-gravity approach and one formulation of space-time foam [3]. Moreover, the latter may be reformulated in the D-brane approach [8]. This is because the scattering of ordinary matter, in the presence of a microscopic 'singular' fluctuation in space-time, requires a quantum treatment of the 'recoil' of the corresponding space-time defect. In string theory, one represents matter as closed string and the defect as a D-brane [5], whose recoil is not described simply by a conformal string background, but rather by a change in the background [8, 9] over which the string propagates.

The resulting string theory becomes ‘non-critical’ [10], flowing from one conformal background to another. This flow is a ‘non-equilibrium’ process, which allows for the formation and evaporation of black holes in a string theory framework [8], and a loss of coherence as argued previously in the framework of space-time foam. This point of view is in agreement with the argument of [11], in the context of the D-brane approach to black holes [5], that pure quantum states cannot form black holes, implying that the formation and evaporation of black holes must be understood within the framework of quantum decoherence.

The central feature of non-critical string is the appearance of a Liouville field on the world sheet, which we identify as a dynamical renormalization scale that we can in turn identify as the physical time [8, 7]. Quantum fluctuations in the space-time background, that are represented by couplings on the string world sheet, induce renormalization via the Liouville field. The corresponding renormalization-group equation has precisely the form (1) postulated previously in the space-time-foam approach. Moreover, the elevation of time to a quantum variable leads to non-trivial uncertainty relations between Liouville time and and the collective space coordinates Y^i of D branes, parallelling and extending the non-commutative geometry of [6].

In the rest of this essay, we explore whether it may be possible to test experimentally such ideas about the quantum-gravitational structure of space-time. We are interested in signatures that are characterized by deviations from conventional quantum mechanics and quantum field theory, that would presumably be suppressed by some power or exponent of the Planck Mass $M_P \sim 10^{19}$ GeV. As we discuss below, several such effects may be at the edge of observability if the suppression is just by a single power of M_P. This might indeed be the case, since the extra term $\not\delta H$ in (1) may have the generic magnitude $\mathcal{O}(E^2/M_P)$ [12]. Similar estimates have been made in the contexts of black holes and D-branes [13, 8], and in the loop-gravity approach [14].

We discuss first the possible effects of a quantum-gravitational environment on the propagation of a massless particle such as a photon. The recoil of a massive space-time defect, modelled as a D-brane, curves space-time, giving rise to a gravitational field of the form [8]:

$$G_{ij} \sim \eta_{ij} + \mathcal{O}(\frac{E}{M_P}) \tag{2}$$

where $E \ll M_P$ is the photon energy, and η_{ij} is a flat Minkowski metric. The most important effect of such a distortion of space-time is the appearance of an induced index of refraction: the effective (group) velocity v of photons in the quantum-gravitational ‘medium’ depends linearly on energy [15]

$$v = c\left(1 - \mathcal{O}(\frac{E}{M_P})\right) \tag{3}$$

where c is the light velocity in empty space, and the minus sign reflects the fact that there is no superluminal propagation in the D-brane recoil approach to stringy quantum gravity [7, 15, 16]. Such an index of refraction has an energy dependence that is quite distinct from that in a conventional electromagnetic plasma, which decreases with increasing energy.

An analogous effect may arise in the loop approach to quantum gravity [1], if the gravitational degrees of freedom are in a "weave" state $|\Delta>$:

$$< \Delta|G_{ab}|\Delta >= \eta_{ab} + \mathcal{O}\left(\frac{1}{M_P\Delta}\right) \tag{4}$$

where Δ is a characteristic length scale of the system [14]. Maxwell's equations for the propagation of ordinary photons are modified in the presence of such a weave state (4), leading to a modified index of refraction of the form (3). Novelties in the loop-gravity case (4) include the possibility of superluminal propagation and a dependence on the helicity of the photon state, which could lead to characteristic birefringence effects.

Finally, we note that photons with the same energy (frequency) might travel at different velocities, as is suggested by higher-order studies in stringy quantum gravity [16]. This would provide a second possible source of dispersion in a wave packet, beyond that associated with differing frequencies.

It is exciting that the existence of a non-trivial index of refraction or other possible modification in the propagation of photons, due to their interaction with a quantum-gravitational medium, might be testable in the near future, if a suppression E/M_{QG} is valid, with $M_{QG} \sim M_P$. The figure of merit for such tests is $(L \times E)/\Delta t$, where L is the distance of a source of photons of energy E which exhibits structure on a time scale of order Δt. As was pointed out in [17], gamma-ray bursters (GRBs) may have particularly large figures of merit, as some exhibit microstructures around a millisecond, they may emit γ rays in the GeV or even TeV range, and many are now known to be located at cosmological distances. It was estimated in [17] that GRB observations might already be sensitive to a quantum-gravity scale $M_{QG} \sim 10^{16}$ GeV, and suggested that the HEGRA and Whipple air Cerenkov telescopes might be able to improve this sensitivity. The Whipple group has now applied this idea to observations of the active galaxy Markarian 421, establishing a lower limit $M_{QG} > 4 \times 10^{16}$ GeV [18]. A possible HEGRA observation of high-energy γ rays from GRB 920925c might be sensitive to $M_{QG} \sim 10^{19}$ GeV [19], and sensitive future tests could be made with the space experiments AMS and GLAST.

Laboratory experiments with elementary particles may also be used to probe the possible quantum nature of space-time, as parametrized by the modified time-evolution equation (1), for example in the neutral kaon system [3, 8, 20]. Data from the CPLEAR collaboration have been used [21] to set upper limits on the possible decohering effects of the quantum-gravitational environment at the level of $1/(10^{17}$ to $10^{20})$ GeV, and there are prospects for improving these limits in future experiments on neutral kaons and mesons containing bottom quarks. It has also been suggested that interesting limits might be obtainable from experiments on neutrino oscillations [22].

Finally, we point out the possibility that the non-commutative structure of space-time induced by multiple D-branes [7], as well as modified uncertainty relations, might be detectable in atom interferometers [23]. Based on the description of topological defects in space-time as D-branes [8, 7], and the non-trivial connection between D-particle recoil and diffusion in open systems [8], it seems that the non-commutativity of space-time might indeed be testable in experiments of the type discussed in [23].

The above examples indicate that experimental tests of some ideas about quantum gravity might not be so difficult as is often thought. We have sketched in this essay an embryonic experimental strategy capable of putting stringent bounds on quantum-gravitational effects, at least in certain approaches. The challenge for theorists now is to explore further the existing models, and to construct new ones that could provide a more complete guide to our experimental colleagues. The challenge for experimentalists is to prove these ideas wrong, which may not be too difficult. The beginning of the next millennium may already provide exciting opportunities to seek quantum gravity.

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