Classicality, Matter-Antimatter Asymmetry, and Quantum-Gravity Deformed Uncertainty Relations

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Abstract
Some of the recent work on quantum gravity has involved modified uncertainty relations such that the products of the uncertainties of certain pairs of observables increase with time. It is here observed that this type of modified uncertainty relations would lead to quantum decoherence, which could explain the classical behavior of macroscopic systems, and CPT violation, which could provide the seed for the emergence of a matter-antimatter asymmetry.

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1 Introduction

Since a compelling theory encompassing gravity and quantum mechanics has not yet emerged (although substantial progress has been made along certain lines of research, most notably in critical string theory [1, 2] and in canonical quantum gravity [3]), the physics community continues to be tempted by the possibility that such a theory might also provide the resolution to other long-standing puzzles confronting our present description of Nature. In particular, the possibility that “quantum gravity” might solve the problems associated to the quantum-mechanical analysis of macroscopic systems (which we find to behave classically in apparent violation of quantum mechanics) has been considered by several authors. In fact, the emergence of classicality could be attributed to gravitational effects that induce quantum decoherence (see, e.g., [4]).

This Essay is devoted to certain quantum-gravity modified uncertainty relations that have been recently discussed both in heuristic analyses of the measurability of distances in quantum gravity and in the context of quantum-gravity theories based on noncritical strings or quantum Poincarè symmetries. It will be here emphasized that such modified uncertainty relations could lead to quantum decoherence, with the above-mentioned implications for the understanding of classicality, and CPT violation, which could provide the seed for the emergence of a matter-antimatter asymmetry.

The “understanding” of the observed matter-antimatter asymmetry is another long-standing problem of theoretical physics. The theories presently used to describe particle physics do not naturally accommodate an asymmetry of the observed size. A substantial effort has gone into studies (see, e.g., Ref. [5]) that exploit CP violation to generate the asymmetry. CPT violation is not usually considered, since the relativistic field theories describing (non-gravitational) particle physics are necessarily CPT invariant; however, it is well understood (see, e.g., Ref. [6]) that CPT violation would provide a rather natural seed for the emergence of a matter-antimatter asymmetry.

In presenting the line of argument here advocated, an attempt is made in the following of proceeding through intuitive observations concerning the relevant structures, rather than providing detailed/technical analyses, which would go beyond the scope of this Essay. Details concerning the quantum-gravity modified uncertainty relations discussed in the next section and the decoherence mechanism discussed in Sec. 3 can be found in Refs. [7-10]. A detailed study of the CPT-violation mechanism discussed in Sec. 3 together with its implications for the emergence of a matter-antimatter asymmetry will be provided in Ref. [11].

2 Quantum-gravity modified uncertainty relations

The expectation that Heisenberg’s uncertainty relations would have to be modified in order to accommodate (quantum) gravitational effects has been often expressed. This can be justified on several grounds, with the non-covariance of the relations perhaps providing the most intuitive argument. The presence of a natural length scale, the Planck length $l_P$, in the quantum-gravitational context is rather naturally expected to play a role in the modifications. In particular, a common hypothesis (see, e.g., Ref. [4, 5]) is that the Planck length would set an absolute lower bound on the measurability of distances. Such a bound would provide a clear departure from ordinary quantum mechanics, in which any observable can be measured (in principle) with complete accuracy (at the price of loosing all information on a conjugate observable). A rather “conservative” scenario that
accommodates $l_p$ as minimum uncertainty is provided by the following modification of Heisenberg’s space-momentum uncertainty relation (henceforth $\hbar \sim c \sim 1 \sim 2$)

$$\delta x \delta p \geq 1 + l_p^2 \delta p^2.$$  \hfill (1)

Relations of type (1) have been quite extensively investigated, especially in light of their relevance for critical string theory, in which evidence in support of the relation (1), but with $l_p$ replaced by the string length $l_s$, is found in the analysis of high-energy string scattering [13].

Even within the framework of critical string theory, more drastic modifications of quantum mechanics have been considered; in particular, the possibility of non-trivial space-time uncertainty relations of the type

$$\delta x \delta t \geq l_s^2$$  \hfill (2)

has been studied in detail [14].

The issue of modified uncertainty relations continues to be quite central in critical string theory, and the recent developments [4] in the understanding of non-perturbative structures have already been exploited from this point of view. Both (1) and (2) have been reanalyzed in recent studies [13, 16] of the soliton-like structures known as Dirichlet p-branes [4], and, interestingly, evidence has been found [15] in support of the idea that “D-particles” (Dirichlet 0-branes) could probe the structure of space-time down to scales shorter than the string length, raising the possibility that (1) might have to be modified.

In parallel with these developments in the literature on critical string theories and conventional quantum-gravity approaches, there have been studies of modified uncertainty relations in the context of models of quantum gravity that support quantum decoherence, such as certain non-critical string theories [17] and certain theories based on quantum Poincarè symmetries [18]. It is this side of the debate on quantum-gravity modified uncertainty relations that is relevant for the mechanisms advocated in this Essay. The emergent general expectation is that decoherence effects should cause the uncertainties characterizing a measurement procedure to grow with the time required by the procedure. In particular, as discussed in Ref. [8], the fact that gravitational effects prevent one from relying on classical agents for the measurement procedure, leads to the following bound for the measurability of a distance $L$:

$$\min [\delta L] \sim \sqrt{\eta T} \sim \sqrt{\eta L},$$  \hfill (3)

2As emphasized in Ref. [8], “classical” (i.e. infinitely massive) devices, whose position and velocity are both completely determined, would lead to inconsistencies associated with the formation of horizons. It is worth noticing that the infinite-mass limit is crucial for ordinary quantum mechanics, which after all is a theory describing the results of experiments in which classical devices observe properties of a microscopic system. The fact that the infinite-mass limit should not be viable in quantum gravity, besides having the implications for the measurability of distances discussed in Ref. [8], can be expected to affect also the measurability of the gravitational field. In the famous analysis by Bhor and Rosenfeld [19], which established that the electromagnetic field is measurable with complete accuracy in ordinary quantum mechanics, a crucial role is played by classical probes, i.e. ideal probes whose ratio of electric charge versus inertial mass can be taken to zero. Although we don’t have a fully satisfactory quantum gravity, we can expect that the gravitational field be not measurable with complete accuracy, since the equivalence principle demands that for all probes the ratio of gravitational charge versus inertial mass be 1. Some work relevant to this line of argument can be found in Ref. [20].

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where \( \eta \) is a (dimensionful) parameter characterizing the spatial extension of the devices (e.g., clocks) used in the measurement, \( T \) is the time needed to complete the procedure of measuring \( L \), and the right-hand side takes into account the fact that \( T \) is typically proportional to \( L \). A candidate modified space-momentum uncertainty relation that leads to the bound (3) is given by

\[
\delta x \delta p \geq 1 + \eta T \delta p^2,
\]

(4)

but the space-time uncertainty relation

\[
\delta x \delta t \geq \eta x \sim \eta t
\]

(5)

would lead to the same bound as a result of its implications for the measurement of distances.

Besides the measurement analyses reported in Refs. [8, 10], and the related studies [7], evidence for bounds of type (3) have been found directly in certain approaches to quantum gravity. In particular, an uncertainty relation of the form (4) appears to characterize Liouville (non-critical) string theories, upon the interpretation of the Liouville mode as the target time [17], while an uncertainty relation of the type (5) has emerged in the context of studies of the quantum \( \kappa \)-Poincaré group [18], which could play a role in the description of the nature of geometry at distances not much larger than the Planck length.

3 Decoherence and CPT violation

While in the previous section I emphasized that the measurability bound (3), and uncertainty relations such as (4) and (5), could naturally emerge in theories supporting quantum decoherence, I now want to clarify that in turn it is also true that quantum decoherence is induced in formalisms involving this type of relations. This is discussed at length in Ref. [7]; however, it is worth illustrating it here at an intuitive level. Let us take for example the uncertainty relation (4). A system prepared as a pure state completely localized at \( x = x_0 \) would accordingly evolve into a (mixed) state with \( x = x_0 \pm \sqrt{\eta t} \). Quantum coherence would therefore be destroyed (at least in the sense of ordinary quantum mechanics).

In order to show that relations such as (3), (4), and (5) naturally lead to CPT violation it is useful to investigate field theories in accordingly deformed phase spaces. A detailed analysis of this issue (within the limitations set by the present poor development of such field theories [21]) will be reported in Ref. [11]. [Related results can also be found in the studies of the relation between decoherence and CPT violation reported in the Refs. [22, 23].] Consistently with the general tone of this Essay, here I try to present an intuitive argument illustrating the emergence of CPT violation when structures of the type discussed in the preceding section are present. This argument requires that alongside the space-momentum uncertainty relation (4), the corresponding time-energy uncertainty relation

\[
\delta t \delta E \geq 1 + \eta t \delta E^2
\]

(6)

should also hold. This would be in analogy with the situation in ordinary quantum mechanics, in which a time-energy uncertainty relation does hold alongside Heisenberg’s
space-momentum uncertainty relation. Assuming (6) one would then expect the lifetime \( t \) of an unstable state to be related to the average lifetime \( \tau \) (time uncertainty) of an ensemble of such states and the corresponding level width \( \Gamma \) (energy uncertainty) by

\[
\Gamma \sim \frac{1}{\tau} + \frac{\eta}{\tau^3} t.
\]  (7)

This equation is formally equivalent to one that could be obtained by introducing time-dependent decay rates, i.e. time-dependent couplings. It is therefore not surprising that a formalism supporting (7) would violate CPT invariance. (Naively antiparticles propagate backward in time, and therefore time-dependent couplings can affect particles and antiparticles differently.)

The idea of quantum-gravity induced CPT violation is actually not so foreign to the quantum-gravity literature. In particular, the type of non-locality advocated in Ref. [24] and the description of the space coordinates as macroscopic variables of a statistical system discussed in Ref. [25] provide other frameworks in which CPT violation could emerge naturally.

4 Closing remarks

This author has here failed to resist the common temptation of hoping that quantum gravity might provide the resolution to several long-standing puzzles confronting our present description of Nature. From this point of view some of the structures discussed in Sec.2 have been found to be quite promising, most notably for decoherence (classicality) and CPT violation (matter-antimatter asymmetry), and this should encourage further exploration of the related physics. However, the approaches to quantum gravity in which evidence of such structures has emerged, such as noncritical string theory and field theory with \( \kappa \)-deformed Poincaré symmetries, are still very poorly developed, and it cannot be excluded that the complete understanding of such approaches would not support any of the relations (3), (4), and (5).

Critical string theory, while being the quantum-gravity approach whose development has been most successful, does not appear to accommodate naturally an intrinsic microscopic mechanism for decoherence or a scenario for the emergence of a matter-antimatter asymmetry. In general, critical string theory appears to provide a rather conservative (while blessed by the emergence of remarkable mathematical structures) modification of our understanding of nature. This is reflected in the “conservative” deformation (4) of Heisenberg’s uncertainty relation and in the nature of the recent stringy understanding [26] of the black hole “paradox”.

\[3\] However, whereas Heisenberg’s operatorial space-momentum uncertainty relation is rooted deep into the formalism, the time-energy uncertainty relation comes in at a somewhat less fundamental level, and cannot be interpreted as an operatorial relation.
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