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On the Status of the Equivalence Principle in Quantum Gravity

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PROJECT ABSTRACT: We argue that further substantial advancement in quantum gravity may remain elusive until a clarification of crucial conceptual problems is achieved. In particular, we believe that a fundamental resolution for the status of the equivalence principle in the quantum domain could prove to be central towards a solution of such conceptual problems. We critically analyze the scenario of enunciating a quantum version of the equivalence principle as well as the possibility of it being an emergent phenomenon with no fundamental counterpart in quantum gravity. We explore the issue from the point of view that *all* our information of the properties of spacetime comes from its interaction with *quantum* matter and that the notion of a physical geometry existing independently of the physical objects used to determine it may be a harmful idealizations for the construction of a quantum theory of gravity.

1 Introduction

It is the opinion of a at least a sector of the *fundamental* theoretical physics community that such field is going through a period of profound confusion (see, e.g., [26, 15, 28, 29]). The claim is that we are living in an era characterized by disagreement about the meaning and nature of basic concepts like time, space, matter and causality, resulting in the absence of a general coherent picture of the physical world.

The discovery of general relativity at the begging of the twentieth century signified a radical departure from the classical understanding of the concepts of space and time to the point that such notions lost their immutability and individual identity. A few years later, the formulation of quantum mechanics shattered the classical accounts of matter and causality by introducing fuzziness and indeterminism into their description. Both theories completely destroyed a long-standing consistent picture of the world, replacing it with an amazingly successful, albeit fragmented, description. There is no doubt that by learning quantum mechanics and general relativity one acquires a feeling of gaining deep insights into how nature works; both theories seem to show us something profound about the world. However, both theories also bring along some uncertainty in the conceptual grasp of the fundamental concepts, as in, for example, interpretational issues in quantum mechanics or the debate on the physical meaning of general covariance in general relativity. Moreover, the problem is greatly exacerbated by any attempt to combine quantum mechanics and general relativity into a full theory of quantum gravity, resulting in puzzles like the issue of diffeomorphism invariance and its connection with observables, the problem of time in quantum gravity, the question of initial conditions for the wavefunction of the universe or the information loss paradox.

The effectiveness of the often pragmatic attitude adopted for the most part of the last century is undeniable. It resulted, where it not for gravity, in a complete and extremely accurate description of the world at a fundamental level. Nevertheless, it is conceivable that such attitude will not be productive in the construction of a fundamental description of the gravitational field in the regime in which its quantum mechanical properties, and that of its sources, cannot be disregarded. Through an overemphasis on technical aspects, in detriment of a careful analysis of conceptual issues, physicists have not been able, despite some very promising developments, to yield a fully consistent marriage of the gravitational and quantum realms.

The general attitude of the present proposal is that further significant advancement in the field may remain elusive until crucial conceptual notions are clarified. Only then, with a truly well grounded basis, the construction of a quantum theory of gravity could be attempted in earnest. A crucial step in this direction would be a clarification of the status of the equivalence principle in the quantum domain. A fundamental resolution for this issue may prove to be a necessary preliminary for the construction of a theory of quantum gravity.

The equivalence principle is the basic idea behind the general relativistic (geometrical) description of gravity. It is a fundamentally local concept in the sense that for its formulation[1] one has to use local notions like point or path: "the *path* of a *point* particle does not depend on the mass of the particle" or "locally inertial frames can be constructed about every *point* in spacetime". Quantum mechanics on the other hand is fundamentally nonlocal: quantum objects are intrinsically extended and well defined trajectories cannot be assigned even to structureless point particles. The resolution of this apparent incompatibility of structural foundations is one of the outstanding conceptual difficulties of quantum gravity.

The central objective of the present proposal is to perform an exhaustive analysis of the possible role of the equivalence principle in quantum gravity. In the next section we outline this objective in more detail.

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[1] There are many different versions of the equivalence principle in the literature, see Sec. 2.1 below for details.

2 A quantum equivalence principle?

We start this section with a clear exposition of the problem to be addressed and conclude it with a presentation of some past proposals for its resolution as well as an outlook for possible routes for future work.

2.1 The conflict

As we mentioned in the introduction, the equivalence principle, one of the best tested principles in physics [27], is the empirical foundation of the general relativistic description of gravitation. Over the years, many different versions and classifications of equivalence principles have appeared in the literature (see e.g. [30, 25, 13] and see [22] for an interesting historical account), however, at the heart of all of them always lies the universality of free fall. In most classifications, the weak equivalence principle (WEP) asserts that *all particles experience the same acceleration in a given gravitational field*, or more precisely, *that if an uncharged pointlike test particle is placed at an initial event in spacetime and given an initial velocity there, then its subsequent trajectory will be independent of its mass and composition.* In the context of Newtonian mechanics, this statement is equivalent to the fact that the ratio of the gravitational mass to the inertial mass of any object is a universal value independent of its composition or other properties.

In the hands of Einstein, the WEP became the physical basis of his general theory of relativity. He noted that if all bodies fall with the same acceleration in an external gravitational field, then to an observer in a freely falling reference frame in the same gravitational field, the bodies should be (*locally*) unaccelerated. Thus, the mechanical motions of bodies will behave as if gravity were absent. Einstein then went a step further and postulated that, in such circumstances, not only the mechanical laws, but *all* physical laws should behave as if gravity were absent. Therefore, from the general relativistic point of view, the equivalence principle is not regarded as a circumstantial feature of the gravitational interaction, but as part of the foundations of physics itself. The new principle shaped by Einstein, sometimes called the Einstein equivalence principle states that *all the nongravitational laws of physics are the same in every freely falling frame* or alternately, that *the WEP is valid and that the outcome of any local nongravitational test experiment is independent of the velocity of the freely falling apparatus, and of where and when in the universe it is performed.*

After this point, different classification usually diverge into the strong, semistrong, very strong, medium strong, etc. equivalence principles. In [13] for example, the very strong equivalence principle states that *for every pointlike event of spacetime, there exists a sufficiently small neighborhood such that in every local, freely falling frame in that neighborhood, all the laws of physics obey the laws of special relativity.* We emphasize in any case the importance of precision in stating and differentiating the different equivalence principles, especially for its possible generalizations into the quantum domain. We stress again that in all of its different versions, the equivalence principle is an eminently *local* statement. It always ultimately describes the behavior of systems in *small enough* regions of spacetime, or more precisely, in one spacetime point at a time. In going into a freely falling frame, the action of a gravitational field can only be strictly canceled in a single point, outside of it, the effects of the curvature of spacetime, manifested locally as tidal forces, are present unavoidably.

Quantum mechanics on the other hand is inherently nonlocal. The uncertainty principle at the roots of its foundations puts stringent limits on the localizability of quantum system. Even point particles, for example, can be localized at a single point in space only for a moment after which its wavefunction inevitably starts to spread out. Moreover, effects like entanglement and teleportation clearly show that quantum mechanics cannot be understood as a theory of localized and disassociated systems; often, at the quantum mechanical level, the description of the joint state of two systems is not the same as the sum of the descriptions of the two systems which may omit all important quantum correlations. Furthermore, we must keep in mind that the concept of a "test" object, present in some versions of the equivalence principle, poses serious problems in quantum mechanics. This is because in a quantum mechanical context i) we may not be able to make the energy of a particle as small as we want in order to avoid back-reaction on a background spacetime, ii) we cannot make the momentum of a particle as small as desired and continue to demand localization and iii) objects may be affected by observations and failure to recognize this may result in internal contradictions.

The situation then is that the classical equivalence principle and quantum mechanics seem to be fundamentally incompatible. How could an essentially local principle be valid in a context where the fundamental entities cannot, even in principle, be confined to spacetime points? Is it the case that there exists a generalization for the equivalence principle to the quantum context that surpasses this difficulty or is it that the equivalence principle is only an emergent phenomenon which ceases to be fundamental at the quantum gravitational level. The investigation of these issues is the main objective of this proposal.

2.2 Looking back and ahead

Over the years, a few proposals for a formulation of a quantum version of the equivalence principle have appeared in the literature. In [2] for example, it is argued that in a quantum context, and in the light of the Aharonov-Bohm effect, one should extend the notion of the equivalence principle to include not only the equivalence of inertial forces with real forces, but also the equivalence of potentials of such inertial forces and the potentials of real forces. References [18, 17] start from a path integral in a flat space parametrized with euclidean coordinates and then perform a non-holonomic coordinate transformation in order to obtain a path integral for spaces with curvature and torsion. The coordinate transformation involved is claimed to be a quantum equivalence principle which allows us to generalize the Feynman path integral formula in Cartesian coordinates to non-euclidean spaces. The proposal in [19] is to enunciate a quantum equivalence principle stating that the output of a physical experiment in its input independent form (the part corresponding to the "pure" interaction, independent of any input of the measuring apparatus) may only depend on the chosen initial state and not on the mass parameter appearing in the dynamical equation. With this, they claim to have found a procedure for extracting results from experiments in a way that does not depend on the mass of the quantum system, allowing a geometrization of gravity even in the quantum domain. Further, the idea in [8] is to connect the quantum equivalence principle with the phase shift appearing in the famous COW experiments [14], which measures a possible particle dependency in the relation inertial mass-passive gravitational mass. We feel however, that none of this formulations possesses the strength and generality to serve as a guiding principle in the search for a quantum theory of gravity.

In [4] on the other hand, it is claimed that instead of trying to formulate a quantum equivalence principle, one should try to quantize teleparallel gravity, a theory which leads to the same classical results as general relativity but without requiring any of the equivalence principles. This type of approach may be attractive because it dispenses the need of an equivalence principle in quantum gravity but explains its (supposedly approximate) validity in the classical realm. Note however that there exists some controversy about the consistency of dealing with Dirac fields in teleparallel gravity [23, 20]. Finally, we mention [24] where a different use for the equivalence principle is called upon. It is used as a guide in order to formalize the idea of a quantum superposition of different spacetimes: the most natural local identification between a local region of one spacetime and a corresponding local region of the other would be that in which the free falls (i.e. spacetime geodesics) agree.

Another issue that has been present lately in the literature is the alleged existence of quantum violations of the equivalence principle (see for example [1, 3, 5]). However, while examining such claims, one must be careful for several reasons (see [12] for a critical analysis of this matter). One point of central importance in these discussions is whether gravity maintains its geometrical character at the quantum level and well defined criteria must be provided in order to determine this issue. For example, it is sometimes claimed that the COW experiment exhibits a non-geometric aspect of gravitation since the results are sensitive to the mass of the particles used. However, one must recognize that at the quantum level, the mass of a particle is associated with a geometrical scale, and that, even in the absence of gravity, the mass of a particle determines its propagation. Then, one could count this as a quantum violation of the equivalence principle, or can maintain that the equivalence principle is satisfied as long as the effects of gravity can be canceled by a suitable choice of reference frame [12]. The later option is more in tone, we believe, with the lesson of general relativity that gravitational effects are captured by the Riemann tensor.

Another important point to be kept in mind is the fact that, as we have already mentioned several times, quantum objects are extended and, as such, could be sensitive to departures of spacetime from exact flatness. Then, in such situations one could not argue that the equivalence principle is violated since the principle strictly applies only to infinitely localized systems. A related matter is the claim that the equivalence principle is not fulfilled for particles with internal structure like spin, a consequence of the fact that such particles follow non-geodesic orbits [6]. One must remember however that there are independent indications of a fundamental noncommutativity of the components of the position associated with the spin of a system and that this noncommutativity is thought to reflect an essential limit on its localizability [10], (this is true even in the classical special-relativistic case, see [21], page 161 (Exercise 5.6)).

An interesting idea that we have considered in the past [9, 10, 11], and that could certainly shed light on the status of the equivalence principle in the quantum context, is to try to define a “quantum geometry” by embracing the fact that our information of the properties of spacetime comes from its interaction with quantum matter, and that this “experimental” aspect of geometry must be taken into account (see [15] for convincing arguments in this direction). The idea is to define a geometry solely by the use of operational definitions involving quantum matter and to attempt to extract from them general features of the underlying (quantum) spacetime. A related idea is to probe spacetime with extended classical objects and to seek to construct an “effective spacetime” in which the center of mass of such distributions follows geodesic orbits (see [11] for details). An investigation of the status of the equivalence principle in this situation should be useful for a possible extension into the quantum regime.

On the experimental side, there is an attractive proposal for an experiment that would probe possible non-trivial couplings of curvature to matter fields [7]. More precisely, it explores potential couplings between spinors and the Weyl tensor. The importance of these experiments is that they attempt to detect gravitational tidal effects using quantum mechanical probes (note that COW-type experiments fail to do so [12]). Any findings on this important issue would surely have an impact on investigations on the quantum role of the equivalence principle.

To conclude we comment on the possibility of the equivalence principle, and with it maybe even gravity itself, being an effective phenomenon akin to, for example, the second law of thermodynamics (see for example [16]). In such case it would be clearly inappropriate to attempt a fundamental formulation of the equivalence principle at the quantum level but one would need to be able to recover its general relativistic expression by taking the appropriate limit. In this scenario, the equivalence principle would hold in general relativity, be approximately valid in the semiclassical regime and completely evaporate in the full theory of quantum gravity.

A clear grasp of the deep physical meaning of the equivalence principle allowed Einstein to construct his theory of general relativity. However, two and a half centuries earlier, Newton used the very same equivalence principle to formulate the general principles for his dynamics. It may very well be that the equivalence principle also holds the key for the formulation of a quantum theory of gravity.

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