

### Three Quantum Aspects of Gravity

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It is argued that (a) In the quantum realm test-particle masses have non-trivial observability which induces a non-geometric element in gravity, (b) Any theory of quantum gravity, on fundamental grounds, must contain an element of non-locality that makes position measurements non-commutative, and (c) The classical notion of free fall does not readily generalize to the quantum regime.

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I came across Professor Ta-You Wu in 1976 at the SUNY at Buffalo. He was not only an energetic man in the physics corridors of Fronczak Hall, but the most energetic one. I never saw him taking the elevators, he always walked, no! he ran the steps – he seemed to carry in his mind restless thoughts and had the apparent need to immediately share them, in their raw and unedited intensity, with either a colleague or a student. So these thoughts became the fuel, or so seemed to me, that they fueled his steps. His charm, his child-like affection for physics, his letters written to me while flying at some high altitude in a plane and talking about possible unification of gravity and electromagnetism, are still very fresh in my memory.<sup>1</sup> So much that despite the fact that he and I have had no occasion to meet in person again since those Buffalo days I recently dreamed of him. It was out of such a night dream that it occurred to me, at the invitation of Jen-Chieh Peng, that I write him a letter. What follows is a letter, written sitting at a lower altitude of 7500 feet in Los Alamos – a letter that I hope will invite comments and wisdom of my teacher under whom I began to learn physics and with whom I published my first research paper [1].<sup>2</sup>

For historical reasons the Einstein's theory of gravitation remains clouded in mystery for most students of physics. This myth and mystery, combined with the theory's mathematical beauty, has made, at times, its experts arrogant and rigid in their purely geometrical thinking. Yet, there remain serious physicists who warn against too geometrical a view [2, 3]. Steven Weinberg [2, p. vii], for instance, notes that "... too great an emphasis on geometry can only obscure the deep connection between gravitation and the rest of physics." Moreover, the mere fact that gravitational interaction between two electrons is about forty orders of magnitude weaker than the electromagnetic interaction does

not imply, contrary to the claims by even so distinguished a physicist as Feynman [3], that quantum effects of gravity cannot be studied in the Earth based laboratories. The gravity of Earth is strong enough to result in large observable gravitationally induced quantum interference phases [4, 5].

The geometrical interpretation of gravity in the classical realm, for instance, arises from the fact that all clocks red shift identically when introduced in a given gravitational environment. Here, I review simple conceptual considerations and show that already known elements of quantum mechanics and gravity require that not all clocks red shift identically in the gravitational environment of a rotating source. This introduces an element of non-universality in the red shifting of the clocks and thus suggests a non-geometric element in gravity in the quantum context. Second, I point out that the ‘‘Collapse of wave function’’ and the associated gravitational considerations, imply an intrinsic element of nonlocality in gravity in the quantum regime. These two results place severe constraints on how we imagine the ultimate unification of gravity with other interactions of nature. Finally, I examine in some detail the extension of the notion of free fall to the quantum realm.

Following Sakurai [6] I treat gravity on equal footing with other interactions. This is justified, at the very minimum, in the weak-field limit. The weak-field limit is sufficient, and indeed desirable,<sup>3</sup> for the conceptual matters that I wish to study. In this framework, the classical motion of a test particle of mass  $m$  in the gravitational field produced by a non-rotating source of mass  $M$  is governed by

$$m \frac{d^2 \mathbf{x}}{dt^2} = -m \nabla \phi_{grav}, \quad (1)$$

while in the non-relativistic quantum regime, one finds

$$\left[ - \left( \frac{\hbar^2}{2m} \right) \nabla^2 + m \phi_{grav} \right] \psi = i \hbar \frac{\partial \psi}{\partial t}. \quad (2)$$

The empirically observed equality of the inertial and gravitational masses enters explicitly both in Eqs. (1) and (2), however, this happens in two different ways:

1. The inertial mass appears on the L.H.S. of Eq. (1) as well as in the kinetic term of Eq. (2), while the gravitational mass enters the R.H.S. of Eq. (1) as a force on the one hand, and as an interaction-energy term in Eq. (2), on the other hand.
2. The gravitational potential  $\phi_{grav} = -GM/r$  emerges within the weak-field limit of Einstein's theory of gravitation and is deduced directly from the equivalence principle.

<sup>1</sup> I very much regret that these Wu letters, full of ideas and love for physics, have gotten lost as I moved from one place to another in my own learnings of physics.

<sup>2</sup> As Professor Wu left Buffalo, I took a detour to film school, only returning to physics to obtain my Ph.D. in 1991.

<sup>3</sup> The desirability, in part, arises from the fact that a purely geometric framework can hardly be expected to hint at a non-geometric element. The ultimate relevance of the arguments that are presented here, therefore, lies in their suggestion of experiments. Such experiments are already underway [4, 5].

Sakurai noted that while the test-particle mass cancels out on both sides of the classical equation of motion Eq. (1), this is not the case for the quantum mechanical Schroedinger equation. As a consequence, the experimentally observed gravitationally induced quantum interference in the Collela, Overhauser, and Werner (COW) experiment on neutron interferometry carries explicit information on the test-particle mass (i.e., neutron mass) [4].

In addition, I note that it is  $\nabla\phi_{grav}$  that governs the physics of Eq. (1) while in Eq. (2) it is  $\phi_{grav}$  that is directly operative. However, even this necessary difference is not always sufficient for physically observable consequences. For gravitational environment that is characterized by an essentially constant  $\phi_{grav}$  the classical effects vanish while quantum effects under certain circumstances do not (see below).

Following these observations and inspired by the COW experiment, I recently suggested in collaboration with Burgard that if one considers a state that is a linear superposition of mass eigenstates<sup>4</sup> then each of the mass eigenstate picks up a mass-dependent gravitationally induced phase [9,10]. This phase, which would have been a global factor, and hence devoid of observability for an isolated mass eigenstate, now gives rise to observable relative phases between the various mass eigenstates. Specifically, for neutrinos I noted that the phenomena of neutrino oscillations provides a flavor-oscillation clock and the mass-dependent gravitationally induced phases make this clock red shift as expected on the basis of Einstein's theory of gravitation.

However this universality of the red shift, which is so important for the geometrical interpretation of gravity in the classical realm, breaks down if one considers a linear superposition of spin projections (with different or equal masses) in the vicinity of a rotating gravitational source. The reason for this break down of the universality lies in the spin-projection dependence of the gravitationally induced quantum phases. The details of this argument I presented in Ref. [11].

Sakurai had already noted in Ref. [6, p.126] that "because mass does not appear in the equation of a particle trajectory, gravity in classical mechanics is often said to be a purely geometric theory." Now my recent work summarized here shows that because trajectory of quantum test particles can carry flavor-oscillation clocks (whose beating depends on masses and spin projections of the superimposed mass eigenstates) the non-universal red shifting of these clocks explicitly depends on the test particle. Hence, I suggest that in the quantum realm the theory of gravity contains a non-geometrical element.

The second observation that I wish to report here is that the collapse of a wave function is associated with the collapse of the energy-momentum tensor. Since it is the energy-momentum tensor that determines the spacetime metric, the position measurements alter the spacetime metric in a fundamental and unavoidable manner. Therefore, in the absence of external gravitating sources (which otherwise dominate the spacetime metric), it matters, in principle, in what order we make position measurements of particles [12]. Quantum mechanics and gravity intermingle in such a manner as to make position measurements non-commutative. This then brings to our attention another intrinsic element of gravity in the quantum realm, the element of non-locality.

Whether this non-locality results in the violation of the CPT symmetry is not yet known [13-15].

As a final observation, I note that the classical notion of the free fall in essence is the local equivalence at a spacetime point of acceleration  $d^2\mathbf{x}/dt^2$  and  $g \equiv -\nabla\phi_{grav}$ . This

equivalence remains invariant under

$$\phi_{grav} \rightarrow \phi_{grav} + \phi_{grav}^0, \quad (3)$$

where  $\phi_{grav}^0$  is essentially constant over the spacetime region of experimental interest. However, the gravitationally induced quantum mechanical relative phases are not invariant under such a transformation, and the readings of clocks in classical free fall may not be considered to give readings that correspond to  $\phi_{grav} = 0$ . Clocks in free fall give readings that correspond to an absence of gravitationally induced accelerations (not phases), i.e., to  $\nabla\phi_{grav} = 0$ . Mathematically, (a) The transformation (3) does not alter Eq. (1) whereas it changes Eq. (2), and (b) Vanishing of a gravitationally induced acceleration, i.e.,  $\mathbf{g} = 0$ , in a given frame, does not imply vanishing of the gravitationally induced phases (in the same frame). It is not clear what is the appropriate generalization of the classical free fall to the quantum realm. Many quantum mechanical clocks are driven by mass, or energy, dependent relative phases and red shift via gravitationally induced phases that depend on  $\phi$ . The red shift of clocks based on quantum mechanical phases can be measured in systematic terrestrial experiments. Classical clocks, on other hand, are insensitive in a free fall to the existence of an essentially constant  $\phi_{grav}^0$  – so, at least, is the case within the general relativistic framework.<sup>5</sup> The question raised here is far from being irrelevant experimentally. In the latest neutron interferometry experiments a discrepancy between theory and experiments continues to exist at the several standard deviation level [16]. I suggest that the observed discrepancy may be pointing not towards some yet unknown systematic errors in the experiments but is indicative of a non-vanishing  $\phi_{grav}^0$ . A non-zero  $\phi_{grav}^0$ , that is essentially constant over the scale of the solar system (say), can easily arise from the cosmological distribution of matter.

I conclude by noting that there is a non-geometric element in gravity in the quantum realm and that any theory of quantum gravity, on fundamental grounds, must contain an element of non-locality that makes position measurements non-commutative. The fundamental notion of free fall, so intricately connected to the principle of equivalence, itself requires further study in the quantum regime. The general observation can therefore be made that the general theory of relativity arose out of the data on planetary orbits. These orbits are determined entirely by the gradient of the gravitational potential, and are insensitive to any contribution to the potential by the cosmological sources. This insensitivity arises because on the length scales of the solar system, or even galactic regions of spacetime, the cosmological contribution to the gravitational potential is constant to a very good accuracy. However, quantum effects remain capable of measuring this cosmological potential. But, general theory of relativity rules out any physical consequences from an essentially constant gravitational potential. Therefore, the inevitable conclusion is reached that in the quantum realm general relativity must suffer fundamental changes. The three quantum aspects of gravity discussed here point towards the conceptual nature of these changes.

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<sup>4</sup> Such states indeed exist in Nature: the  $K - \bar{K}$  system, and neutrinos that are now experimentally indicated to be linear superposition of mass eigenstates [7, 8], provide two such examples.

<sup>5</sup> In the free fall the general-relativistic spacetime metric is  $\eta_{\mu\nu}$ , in the notation of Ref. [2], and therefore  $\phi_{grav}^0$  does not contribute to red shift of the clocks within general relativistic framework.

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