Appendix C: Can Gravity be Quantized?

Vesselin Petkov

Institute for Foundational Studies 'Hermann Minkowski'
Montreal, Quebec, Canada
http://minkowskiinstitute.org/
vpetkov@spacetimesociety.org

Abstract

It may turn out that we have been stubbornly ignoring a crucial message coming from the unsuccessful attempts to create a theory of quantum gravity – that gravity is not an interaction. This option does not look so shocking when gravity is consistently and rigorously regarded as a manifestation of the non-Euclidean geometry of spacetime. Then it becomes evident that general relativity does imply that gravitational phenomena are not caused by gravitational interaction. The geodesic hypothesis in general relativity and particularly the experimental evidence that confirmed it indicate that gravity is not a physical interaction since particles which appear to interact gravitationally are actually free particles whose motion is inertial (i.e. interaction-free). This situation has implications

for two research programs – quantum gravity and detection of gravitational waves. First, the real open question in gravitational physics appears to be how matter curves spacetime, not how to quantize the apparent gravitational interaction. Second, the search for gravitational waves should explicitly take into account the geodesic hypothesis according to which orbiting astrophysical bodies (modelled by point masses) do not radiate gravitational energy since their worldlines are geodesics representing inertial (energy-loss-free) motion.

6.1 Introduction

Since the advent of general relativity and quantum mechanics their unification has been the ultimate goal of theoretical physics. So far, however, the different approaches aimed at creating a theory of quantum gravity [1] have been unsuccessful. It seems a possible reason for this – that gravity might not be an interaction – has never been consistently examined. What also warrants such an examination is that an experimental fact – falling bodies *do not resist* their apparent acceleration – turns out to be crucial for determining the true nature of gravitational phenomena, but has been effectively neglected so far. Taking it into account, however, makes it possible to refine not only the quantum gravity research (by recognizing that the genuine open question in gravitational physics is how matter determines the geometry of spacetime, not how to quantize what has the appearance of gravitational interaction) but also to fine-tune the search for gravitational waves by showing that astrophysical bodies, modelled by point masses whose worldlines are geodesics (representing inertial or energy-loss-free motion), do not give rise to radiation of gravitational energy.

As too much is at stake in terms of both the number of physicists working on quantum gravity and on detection of gravitational waves, and the funds being invested in these worldwide efforts, even the heretical option of not taking gravity for granted should be thoroughly analyzed. It should be specifically stressed, however, that such an analysis will certainly require extra effort from relativists who are more accustomed to solving technical problems than to examining the physical foundation of general relativity which may involve no calculations. Such an analysis is well worth the effort since it ensures that what is calculated is indeed in the proper framework of general relativity and is not smuggled into it to twist it until it yields some features that resemble gravitational interaction.

The standard interpretation of general relativity takes it as virtually unquestionable that gravitational phenomena result from gravitational interaction. However, the status of gravitational interaction in general relativity is far from self-evident and its clarification needs a careful analysis of both the mathematical formalism and the logical structure of the theory and the existing experimental evidence.

Taken according to its logical structure general relativity demonstrates that what is traditionally called gravitational interaction is dramatically different from the other three fundamental interactions, successfully described by the Standard Model, and is nothing more than a mere manifestation of the curvature of spacetime. Unlike the electromagnetic interaction, for example, which is mediated by the electromagnetic field and force, the observed apparent gravitational interaction is not caused by a *physical* gravitational field and a gravitational force. By the geodesic hypothesis in general relativity, the assumption that the worldline of a free particle is a timelike *geodesic* in spacetime is "a natural generalization of Newton's first law" [2, p. 110], that is, "a mere extension of Galileo's law of inertia to

curved spacetime" [3, p. 178]. This means that *in general relativity a particle, whose worldline is geodesic, is a free particle which moves by inertia.*

Indeed, two particles that seem to be subject to gravitational forces in reality *move by inertia* according to general relativity since their worldlines are timelike geodesics in spacetime curved by the particles' masses. The acceleration of the particles towards each other is *relative* and is caused not by gravitational forces, but by geodesic deviation, which reflects the fact that there are no straight worldlines in curved spacetime. In general relativity the planets, for example, are free bodies which move by inertia and as such do not interact in any way with the Sun because *inertial motion does not imply any interaction.* The planets' worldlines are geodesics[20], which due to the curvature of spacetime caused by the Sun's mass are helixes around the worldline of the Sun (which means that the planets move *by inertia* while orbiting the Sun).

Therefore, what general relativity *itself* tells us about the world is that the apparent gravitational interaction is not a physical interaction in a sense that two particles, which *appear* to interact gravitationally, are free particles since they move by inertia. This readily, but counter-intuitively explains the unsuccessful attempts to create a theory of quantum gravity – it is impossible to quantize what we regard as gravitational interaction since it simply does not exist according to what the logical structure of general relativity *itself* implies (without importing features to general relativity whose sole justification is the *belief* that gravitational phenomena are caused by gravitational interaction).

Two main reasons have been hampering the proper understanding of gravitational phenomena. The first reason, discussed

[20] Only the center of mass of a spatially extended body is a geodesic worldline.

in Sect. 6.2, is that the profound consequences of the geodesic hypothesis for the nature of gravitational interaction have not been fully realized mostly due to the adopted definition of a free particle in general relativity, which literarily posits that otherwise free particles are still subject to gravitational interaction – an assumption that does not follow from the theory itself. Sect. 6.3 examines the second reason – that since the advent of general relativity there have been persistent attempts to squeeze general relativity and ultimately Nature into the present understanding that gravitational energy and momentum (as energy and momentum of gravitational interaction and field) are part of gravitational phenomena.

6.2 General relativity implies that there is no gravitational interaction

The often given definition of a free particle in general relativity – a particle is "free from any influences other than the curvature of spacetime" [5] – effectively *postulates* the existence of gravitational interaction by almost explicitly asserting that the influence of the spacetime curvature on the shape of a free particle's worldline constitutes gravitational interaction.

However, if carefully analyzed, the fact that particles' masses curve spacetime, which in turn changes the shape of the worldlines of those particles, does not imply that the particles interact gravitationally. There are two reasons for that. First, the shape of the geodesic worldlines of free particles is determined by the curvature of spacetime *alone* which itself may not be necessarily induced by the particles' masses. This is best seen from the fact that general relativity shows both that spacetime is curved by the presence of matter, and that a matter-free spacetime can be *intrinsically* curved. The latter option follows from the de Sitter solution [4] of Einstein's equations. Two test particles in the

de Sitter universe only appear to interact gravitationally but in fact their interaction-like behaviour is caused by the curvature of their geodesic worldlines, which is determined by the constant positive *intrinsic* curvature of the de Sitter spacetime. The fact that there are no straight geodesic worldlines in non-Euclidean spacetime (which gives rise to geodesic deviation) manifests itself in the relative acceleration of the test particles towards each other which creates the impression that the particles interact gravitationally (*test* particles' masses are assumed to be negligible in order not to affect the geometry of spacetime).

Second, the experimental fact that particles of different masses fall towards the Earth with the *same* acceleration in full agreement with general relativity's *"a geodesic is particle-independent"* [3, p. 178], ultimately means that the shape of the geodesic worldline of a free particle in spacetime curved by the presence of matter is determined by the spacetime geometry *alone* and *not by the matter*. This is clearly seen when the central point of general relativity – the mass-energy of a body changes the geometry of spacetime around itself – is explicitly taken into account. The very meaning of changing the geometry of *empty* spacetime by a body is that *the geodesics of the new spacetime geometry are set*. This is so because what essentially determines the type of spacetime geometry is the corresponding version of Euclid's fifth postulate, which is expressed in terms of the geodesic worldlines of the spacetime geometry. Hence a geodesic is particle-independent because a geodesic is a feature of the spacetime geometry *itself*. The fact that the worldline of a free particle is influenced by the curvature of spacetime produced by a body does not constitute gravitational interaction with the body since the shape of the free particle's worldline is not changed by the body's mass-energy – the body curves *solely* spacetime, regardless of whether or not spacetime is empty, because *no additional energy is spent* for curving the geodesic worldline of the free

particle (or in three-dimensional language – no additional energy is spent for making the particle orbit the body or fall onto it). In short, the mass-energy of a body changes the geometry of spacetime no matter whether or not there are any particles in the body's vicinity, and the shape of free particles' worldlines reflects the spacetime curvature no matter whether it is intrinsic or induced by a body's mass-energy.

The essential role of inertial motion in general relativity follows from the basic fact that the existence of geodesics is a feature of curved spacetime *itself* just like the existence of straight worldlines is a feature of flat spacetime. Straight worldlines represent the inertial motion of free particles of *any* mass in flat spacetime and the straightness of their worldlines is regarded as naturally reflecting the spacetime geometry. Analogously, geodesics in curved spacetime represent free particles of *any* mass that move by inertia. The shape of the geodesics also reflects the spacetime geometry and is not an indication of some interaction exactly like the shape of the straight worldlines in flat spacetime is not an indication of any interaction. The equal status of geodesics in flat and curved spacetimes is encoded in the fall of different masses with the same acceleration. By the geodesic hypothesis, their fall is inertial and indeed the motion of falling particles is unsurprisingly similar to motion by inertia in the absence of gravity – particles that move by inertia do so irrespective of their masses.

That a geodesic worldline in curved spacetime represents an *unconditionally* free particle becomes clearer from a closer examination of the geodesic hypothesis itself and particularly from the experimental evidence which proved it.

Newton's first law of motion (i.e. Galileo's law of inertia) describes the motion of a free particle that is not subject to any interactions. Such a particle moves by inertia, which means that it *offers no resistance* to its motion with constant velocity. If

a particle is subject to some interaction, which prevents it from maintaining its inertial motion, the particle *resists* the forced change of its velocity, i.e. the particle resists its acceleration. The particle's reaction and its resistance to the interaction is captured in Newton's third and second laws of motion. The third law reflects the fact that when a free particle is subject to some action it offers an equal and opposite reaction by *resisting* the action. The profound meaning of Newton's second law is that *a force is only needed to overcome the resistance the particle offers to its acceleration.*

It is the intrinsic feature of a particle to move *non-resistantly* by inertia when its motion is not disturbed by *any* influences that constitutes an objective criterion for a free particle. That is, *non-resistant* motion is a necessary and sufficient condition for a particle to be *free. A particle is subject to some interaction only if it resists its motion.*

Galileo's and Newton's law of inertia was first generalized in special relativity by Minkowski who realized that a free particle, which moves by inertia, is a straight timelike worldline in Minkowski spacetime [6]. By contrast, the worldline of an accelerating particle is curved, i.e. deformed. Had this generalization of the law of inertia been carefully analyzed, two immediate consequences would have been realized. First, the experimental fact that acceleration is *absolute*, because it is detectable due to the resistance an accelerating particle offers to its acceleration, finds an unexpected but deep explanation in Minkowski's spacetime formulation of special relativity. The acceleration of a particle is absolute not because the particle accelerates with respect to some absolute space, but because its worldline is curved and therefore *deformed*, which is an absolute geometric property that corresponds to the absolute physical property of the particle's resistance to its acceleration. Second, the resistance an accelerating particle offers to its acceleration can be also given an un-

foreseen explanation – as the worldline or rather the worldtube of an accelerating particle is curved, the particle's resistance to its acceleration (i.e. the particle's inertia) can be viewed as originating from a four-dimensional stress which arises in the *deformed* worldtube of the particle[21] [7, Chap. 9].

Based on Minkowski's rigorous definition of a free particle in special relativity, the above criterion for a free particle can be made even more precise – in three-dimensional language, a free particle does not resist its motion, whereas in four-dimensional (spacetime) language a free particle is a timelike worldtube, which is *not deformed*. And indeed, in Minkowski spacetime straight worldtubes are not distorted, which explains why a free particle, represented by a straight worldtube, offers no resistance to its free or inertial motion. This criterion provides further justification for the geodesic hypothesis in general relativity by clarifying that a timelike geodesic worldtube in curved spacetime, which represents a free particle, is naturally curved due to the spacetime curvature, but is not deformed[22].

The generalized Minkowski definition of a free particle in spacetime (no matter flat or curved) – a free particle is a *non-deformed* worldtube (straight in flat spacetime and geodesic in curved spacetime) – indicates that a geodesic worldline does represent an unconditionally free particle in general relativity. Indeed, no interaction is behind the fact that the worldtube of a free particle in flat spacetime is straight and the same is true for

[21] This explanation of inertia implies that the worldtubes of particles are real four-dimensional objects completely in line with Minkowski's view of special relativity as a theory of an absolute four-dimensional world and particularly with his explanation of length contraction, which would be impossible if the worldtube of a relativistically contracted body were not real, i.e. if it were a mere geometrical abstraction [6] (see also [7, 8]).

[22] Rigorously speaking, this is true only for a small (test) particle. Tidal stresses, caused by geodesic deviation, give rise to some deformation but that is not caused by a gravitational *force*.

a free particle in curved spacetime – no interaction is responsible for *the curved but not deformed* geodesic worldtube of a free particle there (in agreement with the fact that a geodesic worldline is the analog of a straight worldline in curved spacetime).

What is crucial for testing both the geodesic hypothesis and the generalized definition of a free particle in spacetime and for determining the true nature of gravitational phenomena is the experimental fact that particles falling towards the Earth's surface *offer no resistance to their fall*. This essential experimental evidence has been virtually neglected so far, which is rather inexplicable especially given that Einstein regarded the realization of this fact – that "if a person falls freely he will not feel his own weight" – as the "happiest thought" of his life which put him on the path towards general relativity [9].

This experimental fact unambiguously confirms the geodesic hypothesis because free falling particles, whose worldtubes are geodesics, do not resist their fall (i.e. their apparent acceleration) which means that they move by inertia and therefore no gravitational force is causing their fall. It should be particularly stressed that a gravitational force would be required to accelerate particles downwards *only if* the particles *resisted* their acceleration, because *only then* a gravitational force would be needed to *overcome* that resistance.

Thus, the experimental evidence of non-resistant fall of particles is the definite proof of the central assumption of general relativity – that no gravitational force is causing the gravitational phenomena. This experimental evidence is crucial since it rules out any alternative theories of gravity and any attempts to quantize gravity (by proposing alternative representations of general relativity aimed at making it amenable to quantization) that regard gravity as a *physical* field which gives rise to a gravitational *force* since they would contradict the experimental evidence.

The non-resistant fall of particles also confirms the generalized definition of a free particle since their geodesic worldtubes are naturally curved (due to the spacetime curvature) but are *not deformed*. A falling accelerometer, for example, reads zero acceleration (in an apparent contradiction with the observed acceleration of the accelerometer while falling), which is adequately explained when it is taken into account that what an accelerometer measures is the *resistance* it offers to its acceleration. The zero reading of the falling accelerometer proves that it offers no resistance to its fall and demonstrates that it moves by inertia and therefore its acceleration is not absolute (not resulting from a *deformation* of its worldtube); it is *relative* due to its naturally curved, but *not deformed* worldtube (that is, the accelerometer's relative acceleration is caused by geodesic deviation which itself is a manifestation of the fact that the geodesic worldtube of the accelerometer and the worldline of the Earth's center converge towards each other).

The accelerometer does not resist its fall because its absolute acceleration is zero according to general relativity ($a^\mu = d^2x^\mu/d\tau^2 + \Gamma^\mu_{\alpha\beta}(dx^\alpha/d\tau)(dx^\beta/d\tau) = 0$), which reflects the fact that its worldtube is geodesic and is therefore not deformed[23].

[23]Had Minkowski lived longer he might have discovered general relativity (surely under another name) before Einstein. Minkowski would have almost certainly noticed that inertia could be regarded as arising from the four-dimensional stress in the deformed worldtube of an accelerating particle and therefore inertia would turn out to be another manifestation (along with length contraction as correctly explained by him) of the four-dimensionality of the absolute world of his spacetime formulation of special relativity. Then the experimental fact that a falling particle accelerates (which means that its worldtube is curved), but offers no resistance to its acceleration (which means that its worldtube is not deformed) can be explained only if the worldtube of a falling particle is both curved and not deformed, which is impossible in the flat Minkowski spacetime where a curved worldtube is always deformed. Such a worldtube can exist only in a non-Euclidean spacetime whose geodesics are naturally curved due to the spacetime curvature, but

When the accelerometer is at rest on the Earth's surface its worldtube is not geodesic, which by the geodesic hypothesis means that the accelerometer does not move by inertia and therefore should resist its being prevented from maintaining its inertial motion, i.e. the accelerometer should resist its state of rest on the Earth's surface. Before the advent of general relativity that resistance force had been called gravitational force or the accelerometer's weight. As implied by the geodesic hypothesis the accelerometer's weight is the inertial force, which arises when the accelerometer is prevented from moving by inertia while falling. This is also seen from the fact that the accelerometer's worldtube is *deformed* (not geodesic) – the four-dimensional stress in the deformed worldtube gives rise to a static restoring force that manifest itself as the resistance (inertial) force with which the accelerometer opposes its deviation from its geodesic path in spacetime. The concept of inertia in Minkowski's spacetime formulation of special relativity sheds more light on the physical meaning of the equivalence of inertial and (passive) gravitational masses and forces. They are all inertial and originate from the four-dimensional stress arising in the deformed worldtubes of non-inertial particles (accelerating or being prevented from falling) [7, Ch. 9]. So in the framework of relativity the definition of mass as the measure of the resistance a body offers to its acceleration (i.e. to the deformation of its worldtube) becomes even more understandable.

6.3 There is no gravitational energy in general relativity

The second main reason, which has been hampering the proper understanding of gravitational phenomena, is the issue of grav-

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are not deformed.

itational energy and momentum.

Einstein made the gigantic step towards the profound understanding of gravity as spacetime curvature but even he was unable to accept all implications of the revolutionary view of gravitational phenomena. It was he who first tried to insert the concepts of gravitational energy and momentum forcefully into general relativity in order to ensure that gravity can still be regarded as some interaction despite that the mathematical formalism of general relativity itself refused to yield a proper (tensorial) expression for gravitational energy and momentum. This refusal is fully consistent with the status of gravity as non-Euclidean spacetime geometry (*not a force*) in general relativity. The non-existence of gravitational force implies the non-existence of gravitational energy as well since gravitational energy *presupposes* gravitational force (gravitational energy = work due to gravity = gravitational force times distance).

Although the mathematical formalism and the logical structure of general relativity imply that gravitational phenomena are not caused by gravitational interaction, which entails that there are no gravitational energy and momentum in Nature, most relativists regard gravitational energy as a necessary element of the description of gravitational phenomena. This position is based not only on the view, which literally postulates the existence of gravitational interaction and therefore of gravitational energy and momentum, but also on two generally accepted views.

First, the nonlinearity of Einstein's equations has been interpreted to support the assumption that like the electromagnetic field, the gravitational field also carries energy and momentum. However, unlike Maxwell's equations, which are linear because the electromagnetic field itself does not have electric charge and does not contribute to its own source, the gravitational field must contribute to its own source if it carries energy and momentum since in general relativity any energy is a source of gravity.

This would be consistent with the fact that Einstein's equations are nonlinear – the nonlinearity would represent the effect of gravitation on itself. However, this interpretation of Einstein's equations barely hides the major problem of the standard interpretation of generally relativity that there exists gravitational interaction and therefore gravitational field, which has gravitational energy and momentum. According to the prevailing view in general relativity the components of the metric tensor are the relativistic generalization of the gravitational potential. The nonlinear terms in Einstein's equations are the squares of their partial derivatives, so the energy density of the gravitational field turns out to be quadratic in the gravitational field strength just like the energy density of the electromagnetic field is quadratic in the electric and the magnetic fields.

Identifying the gravitational field with the components of the metric tensor seems justified only in the limiting case when general relativity is compared with the Newtonian gravitational theory in order to determine what in general relativity (in that limiting case) corresponds to the gravitational potential and force. However, such an identification in general relativity itself is more than problematic. There is no tensorial measure of the gravitational field in general relativity since it can be always transformed away in the local inertial frame [3, p. 221]. This is problematic because if the gravitational field existed, then as something real it should be represented by a proper *tensorial* expression. For this reason not all relativists are happy with the identification of the components of the metric tensor with the gravitational field. Synge's view on this is well known – he insisted that the gravitational field should be modelled by "the Riemann tensor, for it *is* the gravitational field – if it vanishes, and only then, there is no field" [2, p. viii]. When gravitational phenomena are properly modelled by the spacetime curvature, which as something real is represented by the Riemann curva-

ture tensor, it follows that gravitation (the spacetime curvature) makes no contribution to its own source – Einstein's equations are linear in the Ricci curvature tensor (the contraction of the Riemann curvature tensor) and the scalar spacetime curvature (the contraction of the Ricci curvature tensor). So, when gravitational phenomena are adequately modelled by the spacetime curvature it is evident that the gravitational field is not something physically real, that is, it is not a physical entity. It is a *geometric* field at best and as such does not possess any energy and momentum.

According to the second view there is indirect astrophysical evidence for the existence of gravitational energy. That evidence is believed to come from the interpretation of the decrease of the orbital period of a binary pulsar system, notably the system PSR 1913+16 discovered by Hulse and Taylor in 1974 [10]. According to that interpretation the decrease of the orbital period of such binary systems is caused by the loss of energy due to gravitational waves emitted by the systems. Almost without being challenged (with only few exceptions [11, 12, 13]) this view holds that the radiation of gravitational energy from the binary systems, which is carried away by gravitational waves, has been indirectly experimentally confirmed to such an extent that even the quadrupole nature of gravitational radiation has been also indirectly confirmed.

It may sound heretical, but the assumption that the orbital motion of the neutron stars in the PSR 1913+16 system loses energy by emission of gravitational waves *contradicts general relativity*, particularly the geodesic hypothesis and the experimental evidence which confirmed it. The reason is that by the geodesic hypothesis the neutron stars, whose worldlines are *geodesics*[24],

[24]The neutron stars in the PSR 1913+16 system had been "modelled dynamically as a pair of orbiting point masses" [14], which means that (i) the tidal effects had been ignored and (ii) the worldlines of the neutron stars

move by inertia without losing energy since the very essence of inertial motion is motion without any loss of energy. Therefore no energy is carried away by the gravitational waves emitted by the binary pulsar system. So the experimental fact of the decay of the orbital motion of PSR 1913+16 (the shrinking of the stars' orbits) does not constitute evidence for the existence of gravitational energy. That fact may most probably be explained in terms of tidal friction as suggested in 1976 [15] as an alternative to the explanation given by Hulse and Taylor.

Despite that there is no room for gravitational energy in general relativity, it is an experimental fact that energy participates in gravitational phenomena, but that energy is well accommodated in the theory. Take for example the energy of oceanic tides which is transformed into electrical energy in tidal power stations. The tidal energy is part of gravitational phenomena, but is not gravitational energy. It seems most appropriate to call it *inertial energy* because it originates from the work done by inertial forces acting on the blades of the tidal turbines – the blades further deviate the volumes of water from following their geodesic (inertial) paths (the water volumes are already deviated since they are prevented from falling) and the water volumes *resist* the further change in their inertial motion; that is, the water volumes exert *inertial* forces on the blades. With respect to the resistance, this example is equivalent to the situation in hydroelectric power plants where water falls on the turbine blades from a height (the latter example is even clearer) – the blades prevent the water from falling (i.e. from moving by inertia) and it resists that change. It is that resistance force (i.e. inertial force) that moves the turbine, which converts the inertial energy of the falling water into electrical energy. According to the standard explanation it is the kinetic energy of the falling water (originating from its potential energy) that is converted

as point masses had been in fact regarded as exact geodesics.

into electrical energy. However, it is evident that behind the kinetic energy of the moving water is its inertia (its resistance to its being prevented from falling) – it is the inertial force with which the water acts on the turbine blades when prevented from falling. And it can be immediately seen that the inertial energy of the falling water (the work done by the inertial force on the turbine blades) is equal to its kinetic energy (see *Appendix B: On inertial forces, inertial energy and the origin of inertia*).

Conclusion

The fact that for decades the efforts of so many brilliant physicists to create a quantum theory of gravity have not been successful seems to indicate that those efforts might not have been in the right direction. In such desperate situations in fundamental physics all options should be on the research table, including the option that quantum gravity as quantization of gravitational interaction is impossible because a rigorous treatment of gravity as a manifestation of the non-Euclidean geometry of spacetime demonstrates that there is no gravitational interaction and therefore there is nothing to quantize.

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