How to demonstrate quantum superposition of classical gravitational fields?

M. Pitkänen
Email: matpitka6@gmail.com.
http://tgdtheory.com/.

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Abstract

Marletto and Vedral have proposed that it might be possible to test experimentally whether gravitational field is quantized. Authors claim that weak measurements giving rise to analog of Zeno effect could be used to test whether the quantum superposition of classical gravitational fields (QSGR) does take place. One can however argue that the extreme weakness of gravitation implies that other interactions and thermal perturbations mask it completely in standard physics framework. Also the decoherence of gravitational quantum states could be argued to make the test impossible.

In TGD however situation might change. In zero energy ontology (ZEO) the sequence of weak measurements is more or less equivalent to the existence of self identified as generalized Zeno effect! The value of $h_{eff}/h = n$ characterizes the flux tubes mediating various interactions and can be very large for gravitational flux tubes (proportional to GMm/v_0, where $v_0 < c$ has dimensions of velocity, and M and m are masses at the ends of the flux tube) with $Mm > v_0 m_{Pl}^2$ (m_{Pl} denotes Planck mass) at their ends. This means long coherence time characterized in terms of the scale of causal diamond (CD). The lifetime T of self is proportional to h_{eff} so that for gravitational self T is very long as compared to that for electromagnetic self. Selves could correspond sub-selves of self identifiable as sensory mental images so that sensory perception would correspond to weak measurements and for gravitation the times would be long: we indeed feel the gravitational force all the time. Consciousness and life would provide a basic proof for the QSGR (note that large neutron has mass of order Planck mass!).

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1 Introduction

There was rather interesting article in Nature [B1] (see http://tinyurl.com/ybylck8m)) by Marletto and Vedral about the possibility of demonstrating the quantum nature of gravitational fields by using weak measurement of classical gravitational field affecting it only very weakly. There is also an article in arXiv by the same authors [B2] (see http://tinyurl.com/ybylck8m). The approach relies on quantum information theory.

The gravitational field would serve as a measurement interaction and the weak measurements would be applied to gravitational witness serving as probe - the technical term is ancilla. Authors claim that weak measurements giving rise to analog of Zeno effect could be used to test whether the quantum superposition of classical gravitational fields (QSGR) does take place. One can however argue that the extreme weakness of gravitation implies that other interactions and thermal perturbations mask it completely in standard physics framework. Also the decoherence of gravitational quantum states could be argued to make the test impossible.

One must however take these objections with a big grain of salt. After all, we do not have a theory of quantum gravity and all assumptions made about quantum gravity might not be correct. For instance, the vision about reduction to Planck length scale might be wrong. There is also the mystery of dark matter, which might force considerable motivation of the views about dark matter. Furthermore, General Relativity itself has conceptual problems: in particular, the classical conservation laws playing crucial role in quantum field theories are lost. Superstrings were a promising candidate for a quantum theory of gravitation but failed as a physical theory.

In TGD, which was born as an attempt to solve the energy problem of TGD and soon extended to a theory unifying gravitation and standard model interactions and also generalizing string models, the situation might however change. In zero energy ontology (ZEO) the sequence of weak measurements is more or less equivalent to the existence of self identified as generalized Zeno effect! The value of $h_{eff}/h = n$ characterizes the flux tubes mediating various interactions and can be very large for gravitational flux tubes (proportional to GMm/v_0, where $v_0 < c$ has dimensions of velocity, and M and m are masses at the ends of the flux tube) with $Mm > v_0 m_{Pl}^2$ (m_{Pl} denotes Planck mass) at their ends. This means long coherence time characterized in terms of the scale of causal diamond (CD). The lifetime T of self is proportional to h_{eff} so that for gravitational self T is very long as compared to that for electromagnetic self. Selves could correspond sub-selves of self identifiable as sensory mental images so that sensory perception would correspond to weak measurements and for gravitation the times would be long: we indeed feel the gravitational force all the time. Consciousness and life would provide a basic proof for the QSGR (note that large neutron has mass of order Planck mass!).

2 Is gravitation classical or quantal?

The conflict between general relativity (GRT) in which gravitation has classical description in terms of geometry and quantum theory was noticed very early, certainly already by Einstein, which explains his refusal to accept quantum theory. Feynman crystallized the problem [B1] and was led to suggest that gravitation must be described quantally. The following arguments suggests that classical gravitational fields reducing to space-time geometries in GRT are necessary to describe gravitationally bound states.

1. The electron in atom is de-localized so that one must have also quantum superposition superposition of classical gravitational fields associated with it. This requires allowance of a space of classical gravitational fields, where one has Schrödinger amplitudes. In GRT framework this means allowance of the space of space-time geometries or at least the space of 3-geometries and Wheeler indeed proposed this notion (super-space).

   The same is true in electrodynamics, where pure QED gives wrong predictions for hydrogen atom but the simple model based on classical em fields gives excellent predictions. This can be understood in TGD in terms of the notion of bound states involving fusion of 3-surfaces to single 3-surface connected by magnetic flux tubes serving also as correlates for quantum entanglement.

   From TGD point of view the path integral quantization of quantum field theories was a mistake and prevented the discovery geometrization of field concept in terms of sub-manifold geometry and the notion of WCW generalizing the geometrization of physics program of Einstein to the entire quantum theory.

2. The quantization of gravitation as quantum field theory (QFT) in flat Minkowski space background is not enough. One must replace world with WCW as done in TGD, where worlds correspond to space-time surfaces in $M^4 \times CP_2$. The induction of process for metric and spinor connection geometrizes various fields and the classical worlds are space-time surfaces.

This leads to a completely new vision about gravitation and other interactions consistent with the standard model leading to notions like hierarchy of Planck constants allowing quantum coherence in even astrophysical length and time scales, p-adic physics, and eventually adelic physics as physics of sensory experience and cognition. What is remarkable that the TGD counterpart of ER-EPR correspondence discovered much before ER-EPR states that magnetic flux tubes serve as correlates for negentropic entanglement and are accompanied by fermionic strings.

1. Each interaction is characterized by its own magnetic flux tubes and by the value of Planck constant $h_{eff} = n \times h$ labelling phases of ordinary matter identified as dark matter. h_{eff} actually has number theoretic interpretation in adelic physics [L1, L2].

2. The Planck constant associated with the magnetic flux tube is proportional to the product of corresponding charges at its ends [K1, K5, K3, K2]. For gravitational interaction one has $\hbar_{eff} = \hbar_{gr} = GMm/v_0$, where M and m are masses at the ends of the flux tube and $v_0 < c$ is parameter with dimensions of velocity. For electromagnetic interaction one has $\hbar_{em} = Ze^2Q_1Q_2/v_0$. The value of h_{gr} is much larger than h and h_{em} if one has $Mm/v_0 > m_{Pl}^2$ (m_{Pl} denotes Planck mass). For $Mm < v_0m_{Pl}^2$ one has $h_{eff} = h_{gr} = h$.

   The large values of h_{gr} suggests that gravitational quantum coherence is possible even in astrophysical scales: Nottale [E1] indeed proposed that one can regard planetary orbits as Bohr orbits. The fountain effect of superfluidity could be one example of this [K5]. h_{gr} would be also in key role in living matter.

This argument relies on mere logic and to my opinion makes the notion of WCW (or some analog of it) compelling if one accepts geometrization of gravitation.

3 Zeno effect and weak measurements

The proposal of Marletto and Vedral [B2, B2] is inspired by quantum information theory. Some of the basic notions involved ancilla or probe, gravitational witness, and weak measurement giving rise to an analog of Zero effect.

3.1 Can one test quantum character of gravitation experimentally?

One can also approach the situation purely experimentally by trying to find effects demonstrating the quantum character of gravitation. The basic problem is the extreme weakness of gravitation. It seems that quantum gravitational effects are masked by other interactions and thermodynamical effects.

1. The simplest question is whether particles in gravitational field of say Earth behave quantally in analogy with the behavior in electromagnetic fields. This is found to be case by studying neutrons in the Earth's gravitational field. This finding by the way killed the idea about entropic gravity identifying gravity as thermodynamical effect [K4]. This experiment does not however say anything about whether classical gravitational fields form quantum superpositions.

2. The emission rate of gravitons by elementary particles are extremely low. Hence on cannot test the theory at elementary particle level by measuring graviton emission and absorption or by studying the gravitational counterparts of bound states such as atoms - this if one assumes standard value of Planck constant only. Also the graviton interference effects and effects like Bose-Einstein condensation seem to be impossible to test. In the early Universe strong gravitational fields exist and inflationary period could show quantum gravitational effects. This kind of tests are however indirect. In TGD framework the cosmic string based model for galactic dark can be seen as support for quantum gravitation.

3. The situation changes if one allows the hierarchy of Planck constants. In this case one can have the analogs of atoms as planetary systems. One can argue that quantum character of gravitational bound states solves the analog of infrared catastrophe of hydrogen atom, which led to the birth of atomic physics. The formation of blackhole would correspond to

infrared catastrophe. Dark gravitons with large h_{gr} have large energies $E = h_{gr}f$ and one can even speculate with the possibility of direct observation of low energy dark gravitons as they transform to bunches of $h_{gr}/h = n$ ordinary gravitons [K2].

The experiment testing QSGR should generate a de-localized particle - say superposition of two sharply localized states. This kind of de-localized states appear in atomic and molecular physics and superconductors and Bose-Einstein condensates provide macroscopic variants of these states. One should test whether these states involve QSGR. Standard physics says that for larger objects this kind of de-localized states are not possible.

If one allows hierarchy of Planck constants, in particular $h_{gr} = h_{eff}$ hypothesis, the situation changes. The fountain effect of super-fluidity could be a representative example [K5]. The de-localization of particles at magnetic flux tubes in the phase transition generating dark matter would directly affect the gravitational field created by system and it might be possible detect this change. Quite generally, quantum critical systems would be excellent candidates for demonstrating quantum superposition of classical gravitational fields.

The challenge is how to demonstrate the existence of QSGR. Gravitational interaction is too weak but could hierarchy of Planck constants change the situation somehow?

3.2 The notion of weak measurement

Contrary to my prejudice, the notion of weak measurement (see `http://tinyurl.com/zt36hpb`) makes sense mathematically and is different from the notion of weak values (see `http://tinyurl.com/yc63pygw`), which to my opinion are mathematical nonsense. The idea of weak measurement is to entangle the weakly measured system with probe and measure the state of the probe rather than system repeatedly. If the initial state of probe is strongly localized to some value of the observable measured, the sequence of measurements does not affect much the weakly measured system and one can monitor it.

1. One has tensor product $A \otimes B$ of two systems and weak interaction entangling them and realized by interaction Hamiltonian H, whose exponential gives rise to time evolution. Time evolution consists of periods Δt_n ending by a measurement of some observable x for B giving eigenvalue q. Each period induces a unitary evolution of A by a Hamiltonian, which does not commute with x. The weakness of the interaction and strong localization of the initial state of B imply that A is only weakly perturbed and ancilla B follows its state in good accuracy.

2. In the simplest situation both system A and B are characterized by single commuting observable x analogous to position operator and its conjugate p. A is the system to be monitored and B is the ancilla. The initial state $|\Psi(0)$ of A is arbitrary and the initial state $\Phi(0)$ of the probe B can be assumed to be Gaussian (for instance): harmonic oscillator could be in question.

3. The canonical choice for the interaction Hamiltonian would be $H = kx \otimes p$. Quantum measurement of x for the ancilla (probe) B after time Δt implies a localization to the state $|q\rangle$. After than unitary evolution induces again de-localization and until new position measurement occurs. One can solve the Schrödinger equation and express the outcome of the measurement of the position x for B as

$$\begin{aligned} \Psi(\Delta t)\Phi(\Delta t) &= M_q\Psi(0) \otimes |q\rangle \ , \\ M_q &= \frac{1}{N} \times exp(-ik\Delta tx \otimes p) \ , \\ N &= \sqrt{\langle \Psi(0)|M_q^\dagger M_q|\Psi(0)\rangle} \ . \end{aligned} \tag{3.1}$$

The unitary operator M_q - Kraus operator - depends on position operator x. It has the eigenvalue q as a parameter.

For Gaussian initial state $\Psi(0)$ one has

$$M_q = \frac{1}{(2\pi\sigma^2)^{1/4}} exp((-q-x)^2/4\sigma^2) \ . \tag{3.2}$$

If the measured state is localized around the eigenvalue of x_0 of x, this distribution is peaked around x_0 and also the eigenvalue of the ancilla position q remains near it. One might say that ancilla follows the state of the weakly measurement system. Note that H is only interaction Hamiltonian and contains also part associated with the weakly measured system.

It is important that the unitary evolution induced by $H = kx \otimes p$ does not leave the eigenstate of q invariant but induces shift by x. Therefore the repeated measurements of q imply a stepwise motion in q-space inducing a similar motion for Ψ in A.

Weak measurement brings strongly in mind Zeno effect in which repeated measurement leave the state unaffected. In the recent case this is not the case since H does not commute with position operator of ancilla. Remarkably, the weak measurement is highly analogous to the generalized Zeno effect in zero energy ontology (ZEO) defining self as sequence of "small state function reductions" at the active boundary of causal diamond (CD) and giving rise to the experience about flow of time.

1. Weak measurement could serve as a model for sensory perception following monitoring target. Self indeed consists of sequences of unitary time evolutions in which system entangles with external world although the its state about the passive boundary of CD representing the unchanging part of self is unaffected. Magnetic flux tubes serve as correlates for both entanglement and attention.

2. The members of state pairs at passive boundary of CD remain unaffected. The sequence of small state function reductions ends up with the death of self as "big" state function reduction at opposite boundary of CD takes place. For sub-selves defining mental images this would mean that attention ceases. Self can be said to performing weak measurements as long it lives! As self dies a time reversed self assignable to the opposite boundary of CD is created.

Remark: There is also so called interaction free measurement (see `http://tinyurl.com/y7zq97q2`), which I considered for some years ago as counterpart of self. This hypothesis turned out to be un-necessary. Interaction free measurement does not seem to be quite same as weak measurement.

3.3 Weak measurement induced by measurement of classical gravitational fields

How could one apply weak measurement to monitor gravitational fields and their quantum superpositions?

1. One could consider replacing x and p by some components of classical gravitational field and their canonical conjugates at some point of space. If one could arrange the measurement interaction to be of the form described above, one could follow the state of classical gravitational field and also the quantum superposition for the values of classical gravitational field - say in given position. The expectation of the operator M_q for the state would reveal the distribution in coordinate x characterizing the value of gravitational field. This would however require successful quantization of gravitational fields. Second problem relates to the measurement interaction: how could one arrange it to be of the desired form.

2. Could the measurement interaction be taken to be the gravitational interaction between A and B? Now the positions for two masses m_A and m_B would become observables and measurement interaction would induce motion in A and the distribution of position for the mass m_A would be visible in the unitary operator M_q acting on state Ψ of the target.

   The extreme weakness of gravitational interaction indeed makes it an obvious candidate for witness interaction. Most importantly, the classical gravitational field created by the target at the position of the ancilla appears in the measurement interaction. The weakness however suggests that gravitation as a measurement interaction is masked by other interactions and by thermal noise. The analog of Zeno period is expected to be very short in standard quantum theory.

If I understood correctly, the authors suggests that the occurrence of the analog of Zeno period is used as a manner to demonstrate the superposition of classical gravitational fields. I could not quite follow the argument. Zeno period should be present also when there is no de-localization of masses m_A and m_B. Information about M_q is needed in order to deduce whether de-localization and superposition of classical gravitational fields is present. If gravitational field is purely classical, one cannot even talk about weak measurement.

3.4 What about the situation in TGD?

In TGD situation changes. ZEO and TGD inspired theory of consciousness enter into play. It would be enough to prove experimentally that the notion of self, which is analog of weak measurement period and an outcome of TGD based view about quantum gravitation relying on the notion of WCW and ZEO, makes sense.

1. Not surprisingly, the hierarchy of Planck constants would play a key role. The lifetime T of self is proportional to $h_{eff}/h = n$, and for gravitational flux tubes one has $\hbar_{eff} = \hbar_{gr} = GMm/v_0$. h_{gr} is much much larger than $h_{eff} = h_{em}$ for the flux tubes mediating electromagnetic interactions (note that flux tubes gives rise to the analog of ER-EPR correspondence which I proposed much before ER-EPR).

   For $Mm > v_0 m_{Pl}^2$ dark matter with $h_{gr} > h$ is possible. Interestingly, Planck mass corresponds in living matter to a water blob with size of large neuron. For $v_0 < c$ neurons could define a pair of systems allowing to test the superposition of classical gravitational fields. One could consider de-localization of neurons or systems associated with them. The de-localization of dark particles at magnetic flux tubes might help here since it would re-distribute part of the matter affecting the gravitational field created by it. The detection of gravitational field of neuron might allow to detect this phase transition: neuron would apparently lose part of its weight.

2. The phase transition generating dark matter in say neuronal system might allow detection via the emergence of generalized Zeno effect. Generalized Zeno effect - identifiable as lifetime of self - would serve as a signature of gravitational entanglement. Gravitational Zeno effect - maybe identifiable in terms of sensory perception of gravitational field of target - lasts much longer than its electromagnetic counterpart and its existence would demonstrate that QSGR is real! This would also demonstrate that TGD inspired theories of consciousness and quantum biology, where h_{gr} plays a key role, might have something to do with reality!

The problem of the proposal is that we are not yet able to detect and manipulate dark matter in laboratory for the simple reason that we do not understand it (maybe we do it routinely at the level of biology!).

1. The TGD based conjecture [K5] is that dark matter as $h_{eff}/h = n$ phases of ordinary matter emerges at quantum criticality. Large h_{eff} would make possible long range quantum fluctuations and correlates by scaling up various quantum lengths typically by h_{eff}/h. Therefore the ability to create and control quantum critical systems would be the prerequisite for the proposed test.

2. Various macroscopic quantum systems are excellent candidates for quantum criticality. Superfluids exhibiting fountain effects apparently defying gravitation could be such systems too [K5]. Note that gravitational Compton length $\hbar_{gr}/m = GM/v_0$ does not depend on the m at all (this is implied by Equivalence Principle) so that particles with different masses could form gravitationally quantum coherent state.

3. In biology this kind of systems could be created for some critical values of parameters: living system would be almost by definition quantum critical and metabolic energy feed would be necessary to induce quantum criticality since in general the energies of various quantum states are larger for $h_{eff} > h$, in particular atomic binding energies behave like $1/h_{eff}^2$. DNA, proteins, cell membrane, axonal membranes, and microtubules would represent examples of critical systems. Nervous system would be such system in longer length scale.

REFERENCES

Theoretical Physics

[B1] Marletto C and Vedral V. Witness gravitys quantum side in the lab. *Nature.* Available at `http://tinyurl.com/ybylck8m`, 547(7662), 2017.

[B2] Marletto C and Vedral V. Witnessing quantumness of a system by observing only its classical features. Available at `http://tinyurl.com/y8dxe3fa`, 2017.

Cosmology and Astro-Physics

[E1] Nottale L Da Rocha D. Gravitational Structure Formation in Scale Relativity. Available at: `http://arxiv.org/abs/astro-ph/0310036`, 2003.

Books related to TGD

[K1] Pitkänen M. Does TGD Predict the Spectrum of Planck Constants? In *Hyper-finite Factors and Dark Matter Hierarchy.* Online book. Available at: `http://www.tgdtheory.fi/tgdhtml/neuplanck.html#Planck`, 2006.

[K2] Pitkänen M. Quantum Astrophysics. In *Physics in Many-Sheeted Space-Time.* Online book. Available at: `http://www.tgdtheory.fi/tgdhtml/tgdclass.html#qastro`, 2006.

[K3] Pitkänen M. TGD and Astrophysics. In *Physics in Many-Sheeted Space-Time.* Online book. Available at: `http://www.tgdtheory.fi/tgdhtml/tgdclass.html#astro`, 2006.

[K4] Pitkänen M. The Relationship Between TGD and GRT. In *Physics in Many-Sheeted Space-Time.* Online book. Available at: `http://www.tgdtheory.fi/tgdhtml/tgdclass.html#tgdgrt`, 2006.

[K5] Pitkänen M. Criticality and dark matter. In *Hyper-finite Factors and Dark Matter Hierarchy.* Online book. Available at: `http://www.tgdtheory.fi/tgdhtml/neuplanck.html#qcritdark`, 2014.

Articles about TGD

[L1] Pitkänen M. p-Adicization and adelic physics. Available at: `http://tgdtheory.fi/public_html/articles/adelicphysics.pdf`, 2017.

[L2] Pitkänen M. Philosophy of Adelic Physics. Available at: `http://tgdtheory.fi/public_html/articles/adelephysics.pdf`, 2017.