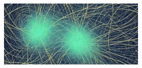
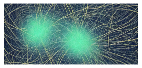


Bohmian Trajectory Gravity - a Better Semiclassical Gravity



Testing Gravity 2023, Thomas C Andersen, tandersen@nscir.ca

Abstract

Semiclassical gravity in the original Rosenfeld formulation has been a very useful tool in quantum gravity studies. We present here Bohmian Trajectory Gravity - which is shown to have advantages over the standard treatment. As an example we show a way to create some entanglement in the BMV experiment with non superposed gravity. Instead of the usual Rosenfeld semi - classical gravity, masses following Bohmian trajectories are employed as the source of the gravitational field. A novel prediction of entanglement for the BMV, and related GIE experiments is a result.

What is Bohmian Trajectory Gravity

Bohmian trajectory gravity is a theory to connect gravity to quantum mechanics that includes the back reaction of matter on quantum mechanics. Like canonical semi classical gravity, it can be used as an approximation to a full quantum theory of gravity.

Semi Classical Gravity [6]

Gravity is non superposed.
Rosenfeld semi classical gravity connects gravity to QM with the expectation value of the wave function.

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}\langle\Psi\,|\,T_{\mu\nu}\,|\,\Psi\rangle$$

$\langle\Psi\,|\,T_{\mu\nu}\,|\,\Psi\rangle$ is the connection to QM.

Gravity has to be able to evaluate the expectation value of the stress/energy of the wave function over all space in real time, no matter the extent of the wave function.

Bohmian Trajectory Gravity [5]

Gravity is non superposed.
Bohmian particle positions connect QM to gravity.

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}(\varphi_B, g)$$

φ_B are trajectories of one member of the ensemble of Bohmian trajectories, and $T_{\mu\nu}(\varphi_B, g)$ is the resulting stress energy tensor. 'g' refers to external fields (earth grav).

Gravity 'merely' has to attach to the hidden position variables of Bohmian QM.

Related/Reference papers

A healthier semi-classical dynamics [2], Layton, Oppenheim, and Weller-Davies

Lays out a generic plan for trajectory based semi classical gravity, of which Bohmian trajectory gravity as presented here is almost, it seems, an example. Provides discussion and examples of advantages to using an ensemble track approach with a single valued gravitational field.

Bohmian quantum gravity and cosmology [7] Pinto-Neto∗and Struyve

Investigates Bohmian approaches to quantum gravity, section 8 contains a few paragraphs on Bohmian trajectory gravity, along with reservations about it.

Is gravitational entanglement evidence for the quantization of spacetime? [3] Döner and Großardt

Provides an explicit counterexample to the claim that only a quantized gravitational field possesses the capability to allow gravitational entanglement experiments (GIE) to show entanglement.

A model of quantum collapse induced by gravity [4] Laloé

Provides a gravitational collapse theory with non superposed gravity connected to Bohmian particle positions

Quantum statistics in Bohmian trajectory gravity [5] Andersen

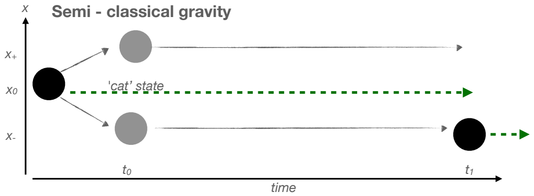
Details how entanglement can arise in GIE experiments with a classical gravity.

Why Bohmian Trajectory Gravity

Many investigations (such as black hole evaporation) need to use both quantum mechanics and gravitation, and it's often the case that perturbative quantum gravity is not developed enough to be of use. So semi classical gravity is used. Often in these investigations, using a track ensemble approach like Bohmian trajectory gravity results in better outcomes. (see Layton, Oppenheim, and Weller Davies [2])

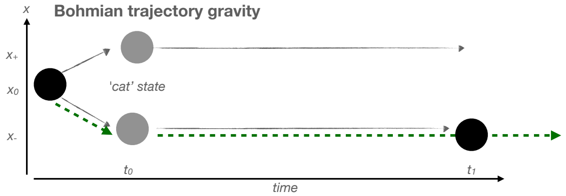
Example: cat state

Create a 'cat' state where a heavy particle is in a superposition of two positions at x_+, x_- at time t_0. Then at time t_1, measure the position. The quantum description is elementary. How does a non superposed gravitational field act?



The creation of the cat state does not change the expectation value of the position operator, so the gravitational field does not change, until at t_1 the measurement (say of x_-) instantly moves the gravitational field to reflect a particle at x_-. There are many problems here, including self attraction, non locality, unexpected behaviour of clocks (time dilation only occurs near the green dashed line), GR shock waves, etc.

These problems arise and can interfere with theoretical results, even where it is acknowledged the semi classical gravity used is an approximation.



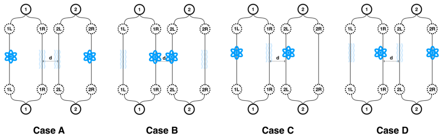
With the creation of the cat state the gravitational field picks one of the paths from the ensemble of possible paths using the Born rule, in this case the field moves to x_-, and at t_1 the measurement reveals the particle at x_-. The gravitational field is not superposed, but the approximation is closer to quantized gravity.

Bohmian Trajectory Gravity as a testable theory quantum gravity

BMV Experiment [10,11] **(Bose, Marletto, Vedral 2017)**

BMV - Experimental proposal to demonstrate that gravity is quantized.

The experiment involves 'massive' ~10^{-14} kg spin 1 objects, which are run through multiple Stern-Gerlach devices. In the diagram 4 runs of the experiment are shown. In Bohmian Trajectory Gravity, each run will look like one of these 4.



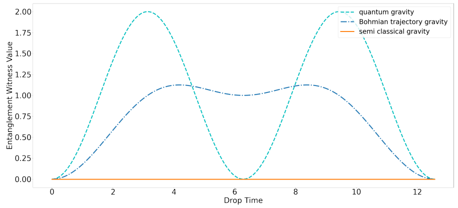
BMV: Entanglement Witness vs Drop Time

In an experiment, one can only measure operator values, not the final wave functions.

For quantum gravity, the chosen entanglement witness operator will peak at a value of 2 when the drop time and other experimental values are arranged correctly. Varying the drop time, the entanglement witness would range from 0 to 2 as drop time is increased from zero.

For Bohmian trajectory gravity, the variation of entanglement with drop time is a differently shaped curve, because there is a weaker contribution from runs C & D. This results in a definitive experimental prediction.

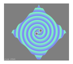
If the experiment fails to maintain coherence or Rosenfeld style semi classical gravity applies, no entanglement will be observed.



With the time scale chosen here, a drop time of 3.14s would result in a maximal signal for quantum gravity, while Bohmian trajectory gravity shows a distinct pattern, a result of the longer time required to build entanglement on paths C and D, combined with the mixing in of entanglement 1/4 of the time in the 'case B' runs.

Gravitational wave radiation by microscopic systems

Atomic quantization: Einstein in 1916

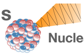


> *Nevertheless, due to the inner-atomic movement of electrons, atoms would have to radiate not only electro-magnetic but also gravitational energy, if only in tiny amounts. As this is hardly true in Nature, it appears that quantum theory would have to modify not only Maxwellian electrodynamics, but also the new theory of gravitation.*

While his prediction for electromagnetism was prescient, perhaps Einstein's 'hardly true in Nature' quip was ill considered. Consider the energy loss rate of a circa 1916 style Bohr planetary hydrogen atom in the ground state, using Eddington's formula for the gravitational energy radiated by a two body system (in the approximation that one mass is much heavier):

$$dE/dt(atom) = -\frac{32Gm_e^2r_h^4\omega^6}{5c^5} = -\,10^{-43}eV/s = 10^{-25}eV \textit{ over the age of the Universe}$$

Why was Einstein worried about such a small rate of gravitational energy loss for a hydrogen atom? In contrast the electromagnetic lifetime of the classical hydrogen atom is about 10^{-11} *s* which of course helped lead to the discovery of quantum mechanics. This GW energy loss is of no experimental significance. So we can conclude that **the stability of atomic orbitals is not an experimental indication of a need for quantum gravity**. In other words we cannot experimentally determine if atoms radiate gravitational waves continuously or not. Of course quantum mechanics demands that atoms do not radiate anything in their ground states, no matter what their angular momentum!



Nuclear/MOND - coincidences

Weinberg, in his 1972 book [16], calculates the thermal gravitational wave emission of the Sun to be about 79 MW at atomic frequencies. In a similar manner, Sivram - Arun[12] calculate the gravitational wave emission from other bodies such as neutron stars. Sivaram - Arun find a rate of 10^{-16} eV/s per neutron. Using the Eddington formula on a Fermi gas model of the nucleus, one arrives at about 10^{-10} eV/s per nucleus.

Gravitational wave fluxes near these levels hint that such effects might be measurable in the lab. If an atomic nuclei emits and/or absorbs on the order of 10^{-16} eV/s (perhaps even per nucleon), then a nucleus might exchange about ~1000 eV over the lifetime of the universe. Bulk effects may become noticeable, since matter has, well, so many nucleons.

It is notable that these classical gravitational wave emission calculations start to make a detectable difference at the same length and energy scales (nuclear/QCD) where our ability to solve the proton/nucleon structure becomes difficult. This is a 'coincidence of uncertainty'.

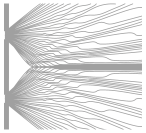
A GW emission of 10^{-10} eV/s per nucleon provides an acceleration of about the MOND acceleration of 10^{-10} m/s^2. Another coincidence.

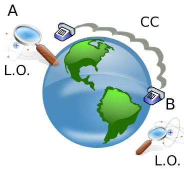
The conclusion we draw from this is that more effort should go into experimentally showing that atoms and nuclei don't emit continuous, weak gravitational waves.

Notes for discussion

Bohmian mechanics has identical predictions to regular quantum mechanics. Thus Bohmian treatments of quantum gravity exist[9].

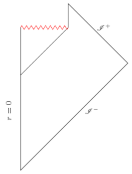
Bohmian trajectory gravity 'breaks' quantum mechanics as do collapse theories (like GRW), etc.

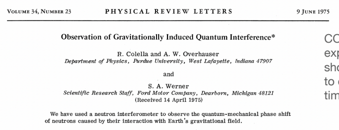




A common objection to the finding here and in other works on entanglement from un quantized gravity is that due to LOCC there can be no entanglement if gravity is classical [11].
In LOCC *a local (product) operation is performed on part of the system, where the result of that operation is "communicated" classically.* LOCC does not hold in Bohmian trajectory gravity, as BT gravity is 'quantum savvy' in the sense that it can see into the (now not so hidden) Bohmian particle positions. Gravity is single valued at all times.

There may advantages to using Bohmian trajectory gravity as a better approximation to quantum gravity than Rosenfeld semi classical gravity. Consider for example effects close to an event horizon or singularity, and how the expectation value approach of semi classical gravity could perform worse than a trajectory ensemble approach, in, say black hole information investigations.





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Observation of Gravitationally Induced Quantum Interference*

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(Received 14 April 1975)

We have used a neutron interferometer to observe the quantum-mechanical phase shift of neutrons caused by their interaction with Earth's gravitational field.

COW experiment[15]: The Colella, Overhauser, and Werner experiment interpreted in terms of Bohmian trajectory gravity shows that gravity affects the paths not taken - this applies directly to case C & D above, where the gravity of one particle affects the time dilation of the other's un-taken path.

References: Please visit https://nscir.ca/testing-gravity-2023-vancouver/ for references/etc - or scan the QR code on your phone.