Bohmian Trajectory Gravity

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We show a way to create entanglement in the BMV experiment with non superposed gravity. Instead of the usual Rosenfeld semi - classical gravity, Bohmian trajectories are employed as the source of the gravitational field. A novel prediction of entanglement for the BMV experiment is a result.

Semi Classical Gravity

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

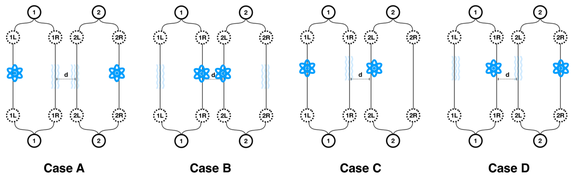
Gravity is non superposed.
Bohmian particle positions connect QM to gravity.

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

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.

BMV Experiment (Bose, Marletto, Vedral 2017)



Experimental proposal to demonstrate that gravity is quantized. We show that substantial entanglement can come from non-superposed gravity.

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.

BMV - Quantum Gravity

Each particle is passed through a typical Stern-Gerlach device, where L and R represent spins in the $\pm x$ direction.

$$|u_1\rangle = \frac{|L_1\rangle + |R_1\rangle}{\sqrt{2}} \quad , \quad |u_2\rangle = \frac{|L_2\rangle + |R_2\rangle}{\sqrt{2}}$$

The product state at the top (t_1) is thus:

$$|\Psi_{t_1}\rangle = \frac{1}{2}\Big(|LR\rangle + |RL\rangle + |LL\rangle + |RR\rangle \Big).$$

The massive particles fall through the apparatus. With quantized gravity, the RL paths are affected: but to only 1 part in 10^{36} by the time dilation of the other, but due to the high Compton frequency of the mass, 10^{36} Hz, this tiny 'delta t' change results in a phase change of π on these paths (ex: ~1s drop). So the phase sign flips on the second term: [1, 2, 3]

$$|\Psi_{t_2}\rangle_{qg} = \frac{1}{2}\Big(|LR\rangle - |RL\rangle + |LL\rangle + |RR\rangle \Big).$$

The fact that the the two states $|u_1\rangle$ and $|u_2\rangle$ are now entangled can be seen by inspection, the state at t_2 is no longer separable. A suitable entanglement witness operator has a value of 2. [9]

BMV - Bohmian Trajectory Gravity

The initial state, $|\Psi_{t_1}\rangle$ is the same as the quantum gravity case. But now we have to look at each of the 4 ensemble paths as different experimental runs. (see 4 cases in diagram).[10]

Case A: No gravitational influence - no state change:

$$|\Psi_{t_2}\rangle_{bt} = \frac{1}{2}\Big(|LR\rangle + |RL\rangle + |LL\rangle + |RR\rangle \Big)$$

Case B: Bohmian particles close together - same final state as quantized gravity:

$$|\Psi_{t_2}\rangle_{bt} = \frac{1}{2}\Big(|LR\rangle - |RL\rangle + |LL\rangle + |RR\rangle \Big).$$

Case C: Right track on 1 affected, other one not:

$$|\Psi_{t_2}\rangle_{bt} = \frac{1}{2}\Big(|LR\rangle + i|RL\rangle + |LL\rangle + |RR\rangle \Big).$$

Case D: Left track on 2 affected, other one not:

$$|\Psi_{t_2}\rangle_{bt} = \frac{1}{2}\Big(|LR\rangle + i|RL\rangle + |LL\rangle + |RR\rangle \Big).$$

We have obtained a mixture of states, which requires a density matrix to evaluate. One can see that 1/4 of the time there is no entanglement, 1/4 of the time we see full entanglement, and the phase change is only partial on case 3 and 4. Final witness operator value is half the QG case (for the initial drop time).

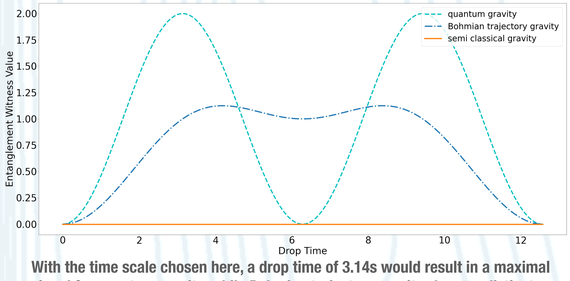
BMV Experiment Entanglement Witness vs Drop Time

In an experiment, one can only measure operator values, not the final wave functions. We assume a noiseless experiment here.

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 3 & 4. This results in a definitive experimental prediction.

If the experiment fails to maintain coherence or 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 3 and 4, combined with the mixing in of entanglement 1/4 of the time in the 'case 2' runs.

Notes for discussion

LOCC: *a local (product) operation is performed on part of the system, and 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 still single valued at all times.

COW experiment: The COW [7] experiment interpreted in terms of Bohmian trajectory gravity shows that gravity affects the paths not taken - this applies directly to case 3 & 4 above, where the gravity of one particle affects the time dilation of the other's un-taken path.

Bohmian trajectory gravity is a break from Bohmian mechanics. Bohmian mechanics has identical predictions to regular quantum mechanics. Thus Bohmian treatments of quantum gravity exist[8]. Bohmian trajectory gravity 'breaks' quantum mechanics as do collapse theories(like GRW), etc.

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 a numerical investigation.

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