A New Experimental Proposal to Test the Nonclassicality of Gravity

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Testing Whether Gravity Acts as a Quantum Entity When Measured

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- Much work on: What is the quantum theory of gravity? What would be the generic features of such a theory?

  Difficult to verify in the laboratory.

- We address a much lower hanging fruit: Whether gravity is quantum mechanical in nature?

  Empirically still unsettled question.

- This seems easier to settle through a laboratory based experiment.

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Objective

What we mean by quantum mechanics:

- **Superposition Principle**
- **Unitary time evolution**
- **Quantum Measurement Postulate**

2017 Proposal aims to test. (Superposition Principle, Unitary time evolution)

Our New Proposal (Quantum Measurement Postulate)

“2017 Proposals”

Featured in Physics

Spin Entanglement Witness for Quantum Gravity

Sougato Bose, Anupam Mazumdar, Gavin W. Morley, Hendrik Ulbricht, Marko Toroš, Mauro Paternostro, Andrew A. Geraci, Peter F. Barker, M. S. Kim, and Gerard Milburn

Phys. Rev. Lett. **119**, 240402 – Published 13 December 2017

Physics See Synopsis: A Test of Gravity's Quantum Side

Featured in Physics

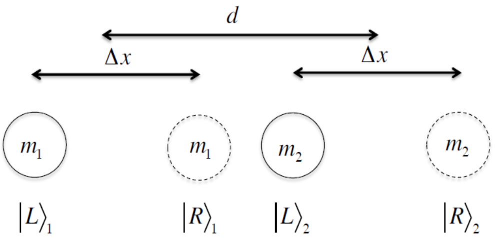
Gravitationally Induced Entanglement between Two Massive Particles is Sufficient Evidence of Quantum Effects in Gravity

C. Marletto and V. Vedral

Phys. Rev. Lett. **119**, 240402 – Published 13 December 2017

Physics See Synopsis: A Test of Gravity's Quantum Side

- Two masses are initially in a product state.

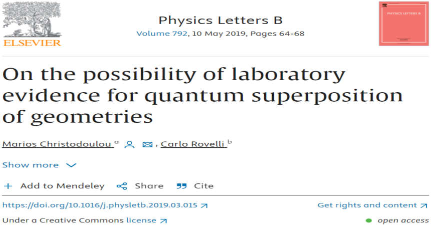


- Entanglement creation between m_1 and m_2 – proof of nonclassical mediator (gravitational field – guaranteed by expt. design) between them.

- Local Operations and Classical Communications (LOCC) cannot entangle[1] – well-known in Quantum Information theory.

[1] Marshman, Mazumdar, Bose, Phys. Rev. A 101, 052110 (2020).

Particular Aspect of Non-classical Gravity to be Tested



- If entanglement is witnessed ⇒ Gravity obeys superposition principle.

Does Gravity obey **Quantum Mechanics**?

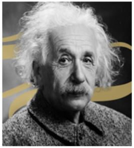
Or, does Gravity obey some **other Non-classical theory** supporting superposition principle?

⇒ **More** Quantum Mechanical Postulates should be tested for Gravity.

Quantum Measurement Postulate

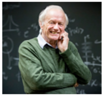
- State Update (Disturbance) on Interaction with Apparatus $\Rightarrow$ We aim to test
- One Measurement Outcome in a Single Run $\Rightarrow$ Always Observed. Nothing *quantitative* to test
- Born Rule $\Rightarrow$ Violation will lead to serious problems!

Definition of Classical Field



Albert Einstein

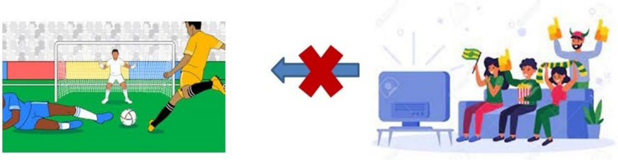
- A number at each point in space-time.
- "In principle" possible to be measured arbitrarily accurately **without** any disturbance.



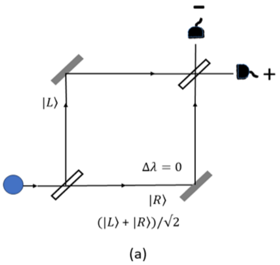
Anthony J. Leggett

Anupam Garg

<u>Non-Disturbance Condition (NDC):</u> The act of performing an intermediate measurement should **not** influence the outcome-statistics of a subsequent measurement.



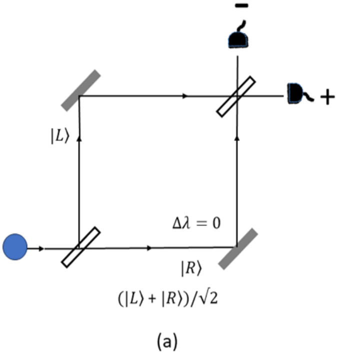
* NDC was originally proposed as the No Signalling in Time condition by J. Kofler and C. Brukner (PRA 2013).



- **Mass is quantum, but large enough to produce a detectable gravitational field at a proximal detector.**
- **Intermediate Measurement [in Fig.(b)] is on Gravity.**

If Gravity is Classical: NDC is satisfied –

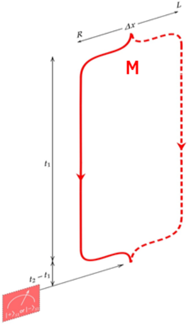
$$P_{\pm}\text{(no intermediate meas.)} = P_{\pm}\text{(after intermediate meas.)}$$

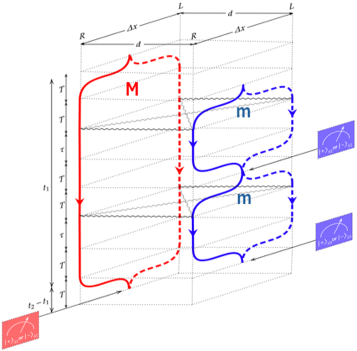


If NDC is *not* satisfied ⟹ **Gravity is Nonclassical:–**

$P_{\pm}$**(no intermediate meas.)** $\neq$ $P_{\pm}$**(after intermediate meas.)**

Specific Proposal





Considering Quantum Gravity: NDC is *not* satisfied –

$$V(\pm) = P_{\pm}(\text{no int. meas.}) - P_{\pm}(\text{after int. meas.}) = f(G, M, m, d, \Delta x, \tau) \neq 0$$

Two probes are taken to *completely remove* a specific *classical disturbance* (disturbance due to measurement even if gravity is classical).

- Mass of the source and each of the probes: $M, m \sim 10^{-14}$ kg,
- Superposition size of the source/probe mass: $\Delta x \sim 250 - 450\ \mu$m,
- Separation between the source and each of the probes: $d \sim 157\ \mu\text{m}^*$,

  * To ensure that gravity is significantly stronger than the electromagnetic (Casimir-Polder) interactions between neutral masses such that the intermediate measurements are indeed on the gravitational field[2].

- Interaction time: $\tau \sim 2 - 3$ s.

$\Rightarrow$ Enough Detectable Nonclassicality: $V_{\pm} \sim 0.4 - 0.5$.

[2] van de Kamp, Marshman, Bose, Mazumdar, Phys. Rev. A **102**, 062807 (2020).

- NDC violation persists for any finite decoherence rate.

  $\Rightarrow$ Unlike the "2017 proposals".

- Does not need trusted measurement devices.

  $\Rightarrow$ Unlike the "2017 proposals".

Experiment: Current Status

We need masses ~ **10^{-14} kg / 10^{-15} kg**.

We need to prepare **pure state** (already achieved by ground state cooling).
Then we need to create **spatial superposition** (**Challenging**).

Experiment is going on in collaboration with

- *Gavin Morley, University of Warwick, UK*
- *Ron Folman, BGU, Israel*
- *Bas Hensen, Leiden University, Netherlands*
- *Andrew A. Geraci, Northwestern University, USA*

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First Challenge: Preparing **Spatial Superposition with Large Masses.**

SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

Realization of a complete Stern-Gerlach interferometer: Toward a test of quantum gravity

Yair Margalit[1*†], Or Dobkowski[1], Zhifan Zhou[1], Omer Amit[1], Yonathan Japha[1], Samuel Moukouri[1], Daniel Rohrlich[1], Anupam Mazumdar[2], Sougato Bose[3], Carsten Henkel[4], Ron Folman[1]

To Conclude...

- Whether gravity is classical or quantum – still an open question!
- The "2017 proposals" can test whether gravity obeys quantum superposition principle.
- Our new proposal can test whether gravity obeys quantum measurement postulate.
- These two tests together take us towards a more complete demonstration of gravity as a quantum entity.
- Compared to the "2017 proposals", our new proposed test has several experimental advantages (robustness to decoherence, no need of trusted measurement devices).

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- **Verifies**

$$\hat{G}_{\mu\nu} = \frac{8\pi G}{c^4} \hat{T}_{\mu\nu}$$

- **Falsifies** Hybrid Models: Quantum Source + Classical Gravity

$$P^{(j)}, \qquad G^{(j)}_{\mu\nu} = \frac{8\pi G}{c^4} T^{(j)}_{\mu\nu} \left(|\psi\rangle_{\text{Source}} \right)$$

Including

$$G_{\mu\nu} = \frac{8\pi G}{c^4} \langle \hat{T}_{\mu\nu} \rangle$$