A New Experimental Proposal to Test the Quantumness of Gravity

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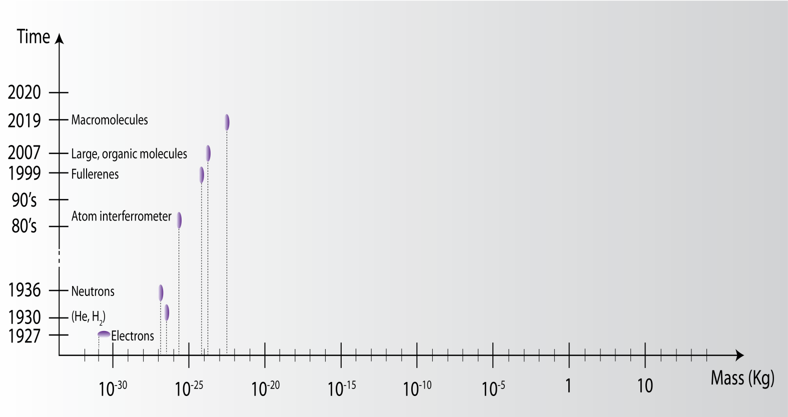
Testing Quantumness of Matter



- These are "Quantum Interference" expts.

- Testing "Spatial Quantum Superposition Principle" with large masses (up to $\sim 10^{-23}$ kg)

Quantum Gravity	Classica Gravity

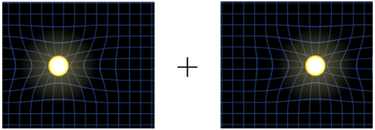
$|L\rangle$ m_1 $|R\rangle$ m_1

Quantum Source of Matter

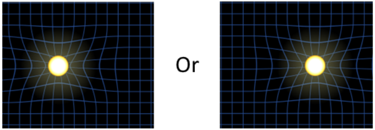
$$|\psi_{\text{matter}}\rangle = \frac{1}{\sqrt{2}} (|L\rangle + |R\rangle)$$

$|L\rangle$ m_1 $|R\rangle$ m_1

Superposition of Spacetimes



Statistical Mixture of Spacetimes



Quantum Theories of Gravity:

(1) String Theory
(2) Loop Quantum Gravity
(3) Canonical Quantization
(4) ...

Classical Theories of Gravity:

(1) Recent Theory by Oppenheim (PRX, 2023)
(2) KLM (Kafri-Taylor-Milburn) Model (NJP, 2014)
(3) Diosi-Halliwell Model (PRL, 1998)
(4) Gravity-induced Collapse Model (Diosi-Penrose)
(5) Moller-Rosenfeld Model
(6) ...

- Much work on: Constructing quantum theories/classical theories of gravity sourced by quantum matter.

  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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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"

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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**, 240401 – Published 13 December 2017

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

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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

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

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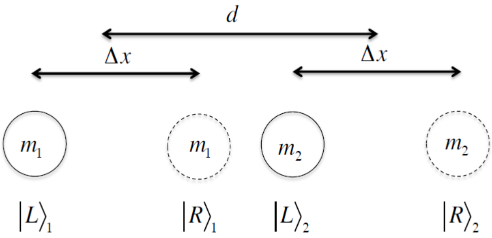
- Two masses are initially in a product state.



- 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); Horodecki, Horodecki, Horodecki, Horodecki, Rev. Mod. Phys. **81**, 865 (2009).

- If decoherence rate $\Gamma >$ certain threshold, no entanglement is generated.

  $\Rightarrow$ The protocol fails.[2]

- For such high decoherence rate, the coherence in the spatial superposition is not completely lost.

Can this remaining coherence be exploited to observe some nonclassicality of gravity?.

[2] Schut, Tilly, Marshman, Bose, Mazumdar, Phys. Rev. A **105**, 032411 (2022); Rijavec, Carlesso, Bassi, Vedral, Marletto, New Journal of Physics **23**, 043040 (2021).

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- The "2017 proposal" requires realizing entanglement witness operators.

  ⇒ Requires completely trusted measurement devices (e.g. σ_x, σ_y, σ_z).

  ⇒ Very difficult in experiments.

- One can bypass this requirement by detecting entanglement through Bell test[3].

  ⇒ This requires even lower decoherence rate[4] and closing various loopholes (very hard).

Can we propose a new experiment to test nonclassical gravity that does not require trusted measurement devices?

[3] Kent, Pitalua-Garcia, Phys. Rev. D **104**, 126030 (2021).

[4] Hanif, Das, Halliwell, Home, Mazumdar, Ulbricht, Bose, arXiv:2307.08133 [gr-qc].

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Particular Aspect of Non-classical Gravity to be Tested by the "2017 Proposals"

Physics Letters B
Volume 792, 10 May 2019, Pages 64-68

On the possibility of laboratory evidence for quantum superposition of geometries

Marios Christodoulou [a], Carlo Rovelli [b]

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Marios Christodoulou, Andrea Di Biagio, Markus Aspelmeyer, Časlav Brukner, Carlo Rovelli, and Richard Howl
Phys. Rev. Lett. **130**, 100202 – Published 10 March 2023

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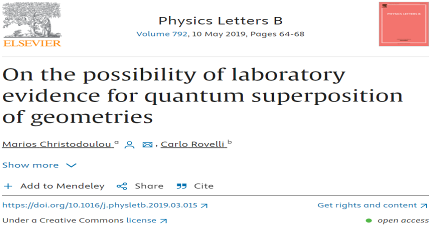
- If entanglement is witnessed $\Rightarrow$ Gravity obeys superposition principle.

Does Gravity obey **Quantum Mechanics**?

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

$\Rightarrow$ **More** Quantum Mechanical Postulates should be tested for Gravity.

Particular Aspect of Non-classical Gravity to be Tested by the "2017 Proposals"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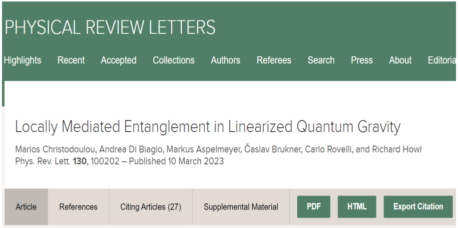
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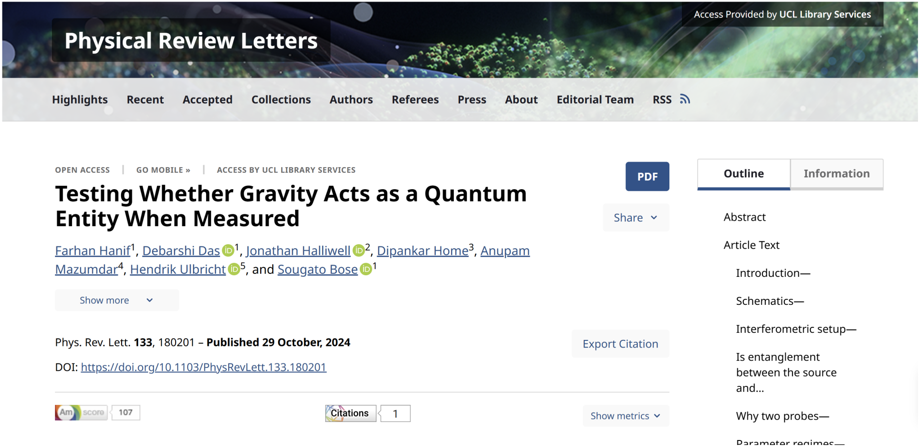
New Proposal



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Testing Whether Gravity Acts as a Quantum Entity When Measured

Farhan Hanif[1], Debarshi Das[1], Jonathan Halliwell[2], Dipankar Home[3], Anupam Mazumdar[4], Hendrik Ulbricht[5], and Sougato Bose[1]

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Phys. Rev. Lett. **133**, 180201 – **Published 29 October, 2024**

DOI: https://doi.org/10.1103/PhysRevLett.133.180201

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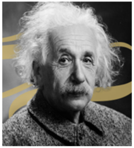
Outline | Information

- Works for any finite decoherence rate.
- Does not require trusted measurement devices.
- Tests a specific aspect of Quantum Measurement Postulate (different from Quantum Superposition Principle).

- Quantum Measurement Induced Disturbance/Collapse $\Rightarrow$ 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!

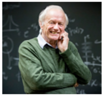
Definition of Classical Field


Albert Einstein


Caslav Brukner

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

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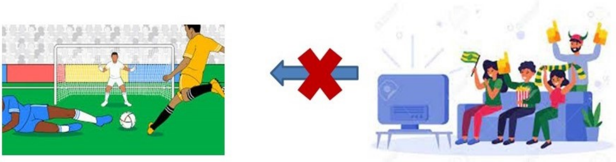
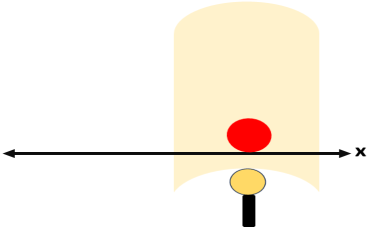
Anupam Garg


Johannes Kofler



- Classical systems can be measured 'in principle' without disturbance.
- In practice, measurement on classical system can cause disturbance $\Rightarrow$ Classical Disturbance.



- Classical disturbance is not an inherent part of classical mechanics $\rightarrow$ Can be reduced arbitrarily.

- Quantum Measurement Induced Collapse/Disturbance is an inherent part of quantum mechanics.
- Cannot be reduced or eliminated.

• Violation of Non-Disturbance Condition (NDC) → Consequence of Measurement Induced Disturbance.

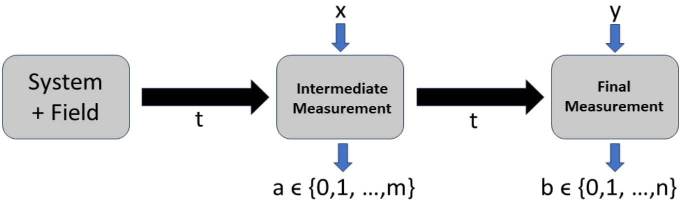
• Showing Violation of NDC after eliminating all possible Classical Disturbances → Genuine Quantum Signature.

- Quantum Measurement Induced Collapse/Disturbance is an inherent part of quantum mechanics.
- Cannot be reduced or eliminated.

• Violation of Non-Disturbance Condition (NDC) $\rightarrow$ Consequence of Measurement Induced Disturbance.

• Showing Violation of NDC after eliminating all possible Classical Disturbances $\rightarrow$ Genuine Quantum Signature.

Non-Disturbance Condition (NDC)[5]



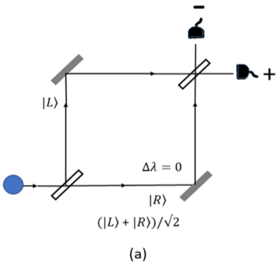
- Intermediate and final measurements may be **different**.
- Each measurement is **either on the field or on the system**.

P_b(No Intermediate Measurement) = P_b(After Intermediate Measurement)

Where P_b(After Intermediate Measurement) = Σ_a P(a,b)

[5] Kofler, Brukner, Phys. Rev. A **87**, 052115 (2013); Knee, Kakuyanagi, Yeh, Matsuzaki, Toida, Yamaguchi, Saito, Leggett, Munro, Nature Communications **7**, 13253 (2016); Schild, Emary, Phys. Rev. A **92**, 032101 (2015).

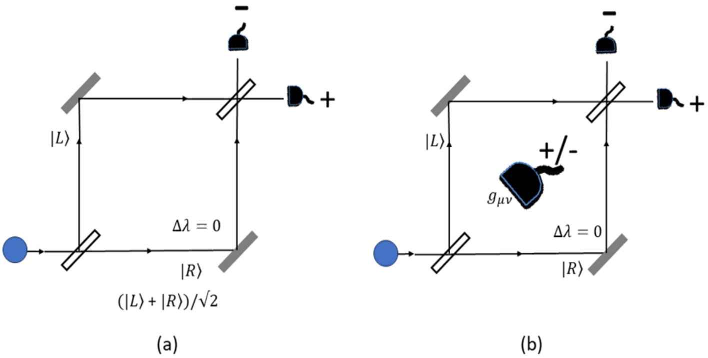
Classical Gravity



- **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 –

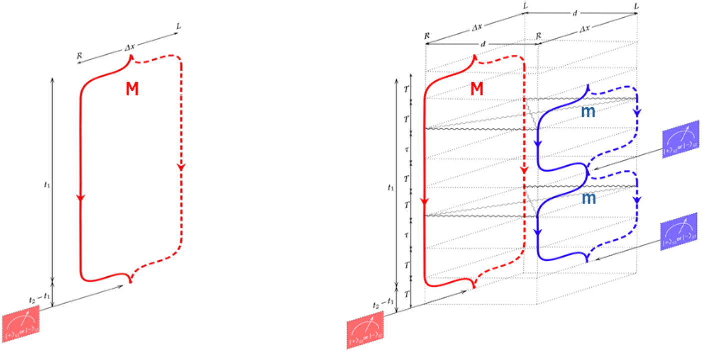
$P_{\pm}$**(no intermediate meas.) =** $P_{\pm}$**(after intermediate meas.)**



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 –

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

To ensure that the intermediate measurement is on gravity: d $\geq 157\mu m$ (considering the system to be diamond with one NV center point, where the electronic spin can be embedded in mass)

Why Two Probes?

One probe:

$$\rho_1 = \frac{1}{2}(1+\cos\Delta\phi)\frac{|L\uparrow\rangle + |R\downarrow\rangle}{\sqrt{2}}\frac{\langle L\uparrow| + \langle R\downarrow|}{\sqrt{2}} + \frac{1}{2}(1-\cos\Delta\phi)\frac{|L\uparrow\rangle - |R\downarrow\rangle}{\sqrt{2}}\frac{\langle L\uparrow| - \langle R\downarrow|}{\sqrt{2}}$$

Equivalent to:

$$\mathcal{R}_z(\theta)[(1+e^{-\beta_2 t})/2\ \mathbb{I} + (1-e^{-\beta_2 t})/2\ \sigma_z]$$

Two probes:

$$\rho_1 = \frac{1}{2}(1+\cos^2\Delta\phi)\frac{|L\uparrow\rangle + |R\downarrow\rangle}{\sqrt{2}}\frac{\langle L\uparrow| + \langle R\downarrow|}{\sqrt{2}} + \frac{1}{2}(1-\cos^2\Delta\phi)\frac{|L\uparrow\rangle - |R\downarrow\rangle}{\sqrt{2}}\frac{\langle L\uparrow| - \langle R\downarrow|}{\sqrt{2}}$$

Equivalent to:

$$[(1+e^{-\beta t})/2\ \mathbb{I} + (1-e^{-\beta t})/2\ \sigma_z]$$

- To cancel classical disturbances on the source mass caused by the gravitational interaction due to the presence of the probe.
- Classical disturbances due to other means (electromagnetic interactions, photon scattering etc.) is eliminated by shielding and other technical ways.

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*

Funded by *UK EPSRC-STFC joint, ERC, Sloan Foundation, Moore Foundation*.

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]

What can be concluded?

If the "2017 Proposal" gives positive result (detecting Gravity-Induced-Entanglement)

Or,

If our "New Proposal" gives positive result (detection of NDC violation)

Quantum Theories of Gravity:

(1) String Theory
(2) Loop Quantum Gravity
(3) Canonical Quantization
(4) ...

~~**Classical Theories of Gravity:**~~

~~(1) Recent Theory by Oppenheim (PRX, 2023)~~
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~~(3) Diosi-Halliwell Model (PRL, 1998)~~
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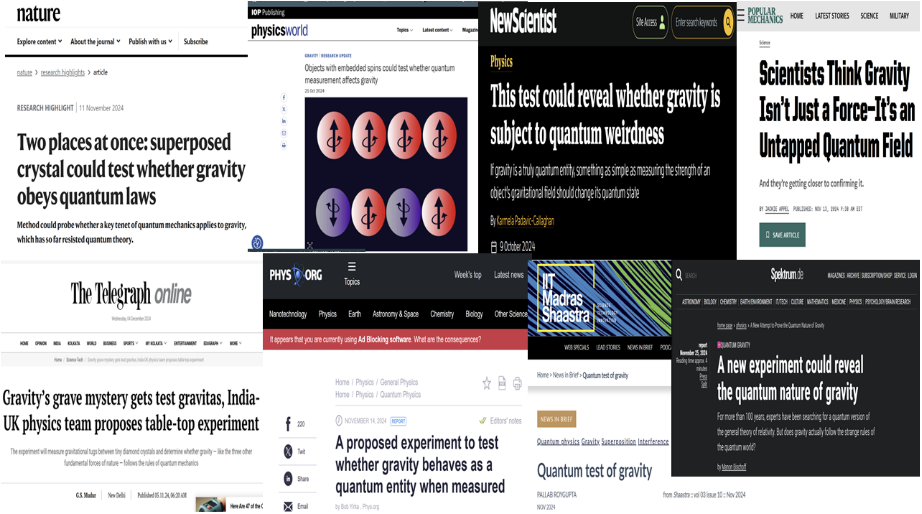
~~(5) Moller-Rosenfeld Model~~
~~(6) ...~~

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 to trust measurement devices).



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Objects with embedded spins could test whether quantum measurement affects gravity

21 Oct 2024

NewScientist

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By Karmela Padavic-Callaghan

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BY JACKIE APPEL PUBLISHED: NOV 13, 2024 9:30 AM EST

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G.S. Mudur | New Delhi | Published 05.11.24, 06:20 AM

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A proposed experiment to test whether gravity behaves as a quantum entity when measured

by Bob Yirka , Phys.org

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QUANTUM GRAVITY

November 25, 2024

A new experiment could reveal the quantum nature of gravity

For more than 100 years, experts have been searching for a quantum version of the general theory of relativity. But does gravity actually follow the strange rules of the quantum world?

by Manon Bischoff

Current State-of-the-Art

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Quantum Physics

[Submitted on 1 Sep 2025]

A Spin-Based Pathway to Testing the Quantum Nature of Gravity

Sougato Bose, Anupam Mazumdar, Roger Penrose, Ivette Fuentes, Marko Toroš, Ron Folman, Gerard J. Milburn, Myungshik Kim, Adrian Kent, A. T. M. Anishur Rahman, Cyril Laplane, Aaron Markowitz, Debarshi Das, Ethan Campos-Méndez, Eva Kilian, David Groswasser, Menachem Givon, Or Dobkowski, Peter Skakunenko, Maria Muretova, Yonathan Japha, Naor Levi, Omer Feldman, Damián Pitalúa-García, Jonathan M.H. Gosling, Ka-Di Zhu, Marco Genovese, Kia Romero-Hojjati, Ryan J. Marshman, Markus Rademacher, Martine Schut, Melanie Bautista-Cruz, Qian Xiang, Stuart M. Graham, James E. March, William J. Fairbairn, Karishma S. Gokani, Joseph Aziz, Richard Howl, Run Zhou, Ryan Rizaldy, Thiago Guerreiro, Tian Zhou, Jason Twamley, Chiara Marletto, Vlatko Vedral, Jonathan Oppenheim, Mauro Paternostro, Hendrik Ulbricht, Peter F. Barker, Thomas P. Purdy, M. V. Gurudev Dutt, Andrew A. Geraci, David C. Moore, Gavin W. Morley

A key open problem in physics is the correct way to combine gravity (described by general relativity) with everything else (described by quantum mechanics). This problem suggests that general relativity and possibly also quantum mechanics need fundamental corrections. Most physicists expect that gravity should be quantum in character, but gravity is fundamentally different to the other forces because it alone is described by spacetime geometry. Experiments are needed to test whether gravity, and hence space-time, is quantum or classical. We propose an experiment to test the quantum nature of gravity by checking whether gravity can entangle two micron-sized crystals. A pathway to this is to create macroscopic quantum superpositions of each crystal first using embedded spins and Stern-Gerlach forces. These crystals could be nanodiamonds containing nitrogen-vacancy (NV) centres. The spins can subsequently be measured to witness the gravitationally generated entanglement. This is based on extensive theoretical feasibility studies and experimental progress in quantum technology. The eventual experiment will require a medium-sized consortium with excellent suppression of decoherence including vibrations and gravitational noise. In this white paper, we review the progress and plans towards realizing this. While implementing these plans, we will further explore the most macroscopic superpositions that are possible, which will test theories that predict a limit to this.

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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

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

- **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

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

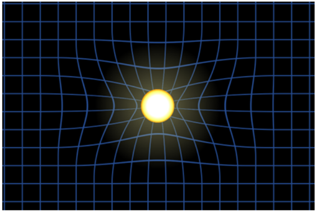
Gravity Sourced by Quantum Matter

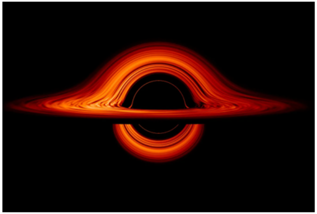
Einstein Field Equation

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

Curvature Tensor
Classical Space-Time

Stress-Energy Tensor
of Matter





Theories of Gravity Sourced by Quantum Matter

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

Examples:

- String Theory
- Loop Quantum Gravity
- Canonical Quantization
- Many More

Stochastic Theories

$$\{ P_j , G^{(j)}_{\mu\nu} \}$$

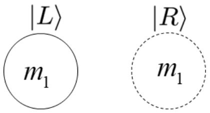
$$G^{(j)}_{\mu\nu} = \frac{8\pi G}{c^4} T^{(j)}_{\mu\nu} (|\psi\rangle_{\text{Source}})$$

Superposition of Spacetimes

Statistical Mixture of Spacetimes

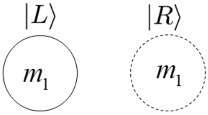
Theories of Gravity Sourced by Quantum Matter

Quantum Gravity	Classica Gravity

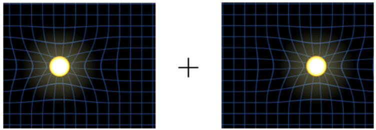


Quantum Source of Matter

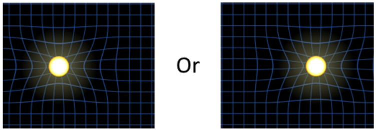
$$|\psi_{\text{matter}}\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle + |R\rangle\right)$$

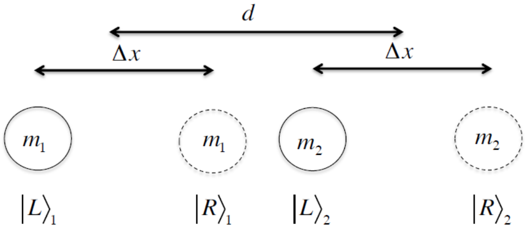


Superposition of Spacetimes



Statistical Mixture of Spacetimes





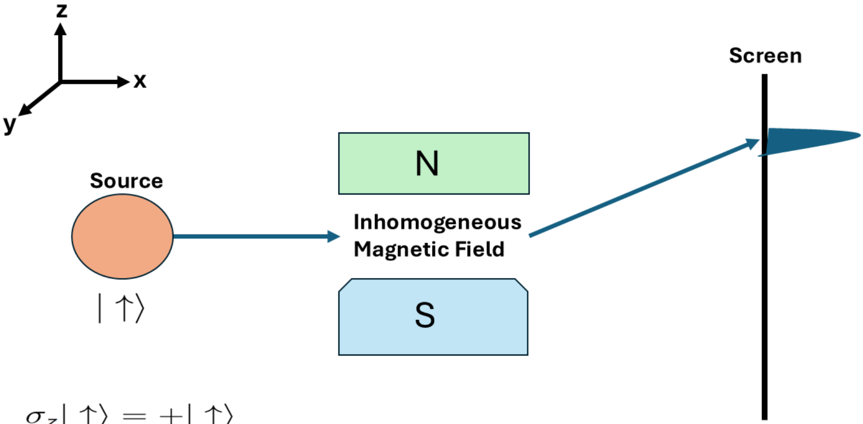
If they interact *only* through the gravitational force

Final state (ignoring overall phase):

$$|\Psi\rangle_{12} = |L\rangle_1 \frac{1}{\sqrt{2}} \left(|L\rangle_2 + e^{i\Delta\phi_{LR}}|R\rangle_2\right) + |R\rangle_1 \frac{1}{\sqrt{2}} \left(e^{i\Delta\phi_{RL}}|L\rangle_2 + |R\rangle_2\right)$$

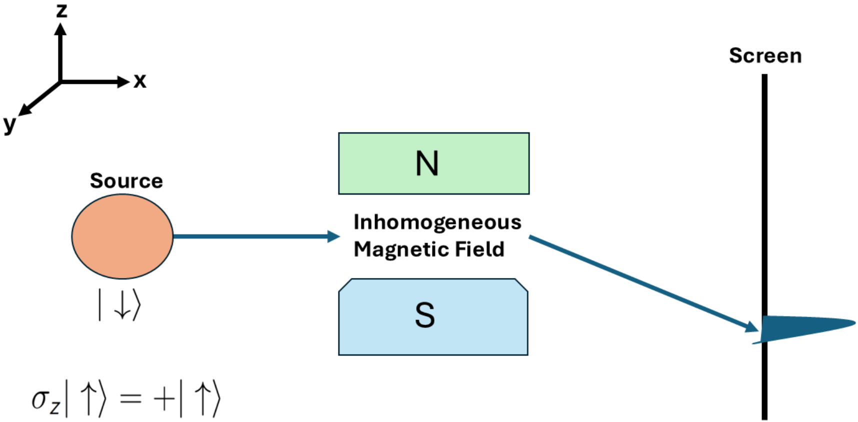
with $\Delta\phi_{LR} = \frac{G m_1 m_2 \tau}{\hbar(d+\Delta x)} - \frac{G m_1 m_2 \tau}{\hbar d}, \; \Delta\phi_{RL} = \frac{G m_1 m_2 \tau}{\hbar(d-\Delta x)} - \frac{G m_1 m_2 \tau}{\hbar d}$

$\Rightarrow$ Entangled for any $\Delta\phi_{LR} + \Delta\phi_{RL} \neq 2n\pi$.



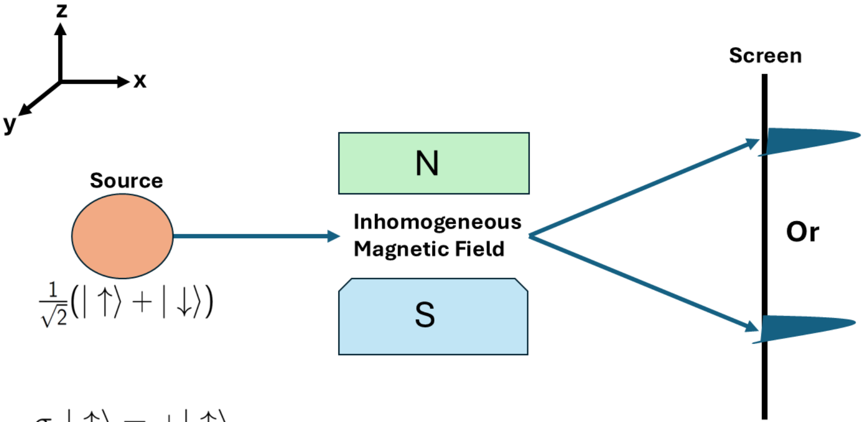
$$\sigma_z | \uparrow \rangle = +| \uparrow \rangle$$
$$\sigma_z | \downarrow \rangle = -| \downarrow \rangle$$

How to do Expt.: Stern Gerlach Setup



$$\sigma_z|\uparrow\rangle = +|\uparrow\rangle$$
$$\sigma_z|\downarrow\rangle = -|\downarrow\rangle$$

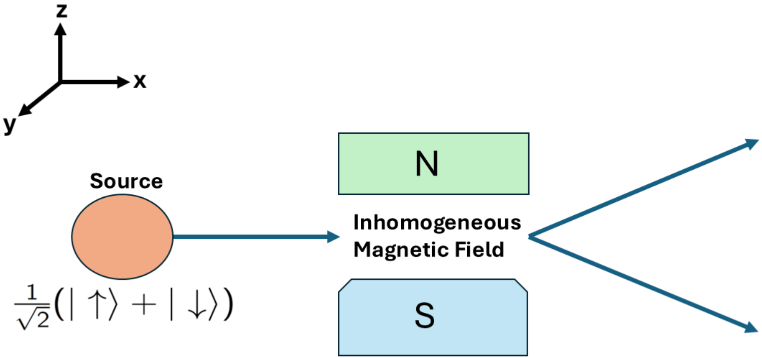
How to do Expt.: Stern Gerlach Setup



$\frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$

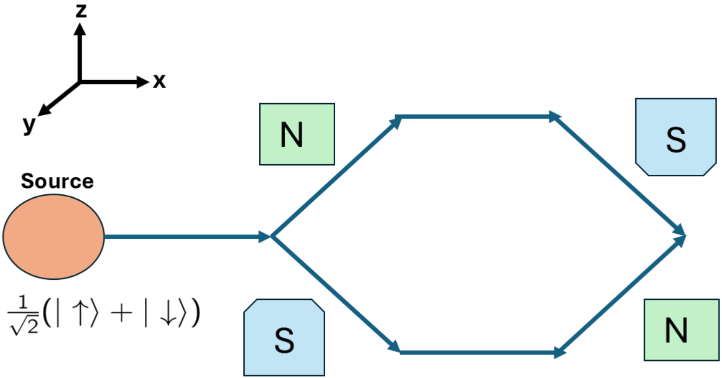
$$\sigma_z|\uparrow\rangle = +|\uparrow\rangle$$
$$\sigma_z|\downarrow\rangle = -|\downarrow\rangle$$

How to do Expt.: Complete Stern Gerlach Interferometry



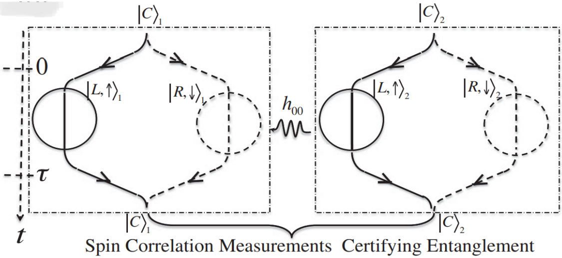
$$\frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$$

$$\sigma_z|\uparrow\rangle = +|\uparrow\rangle$$
$$\sigma_z|\downarrow\rangle = -|\downarrow\rangle$$



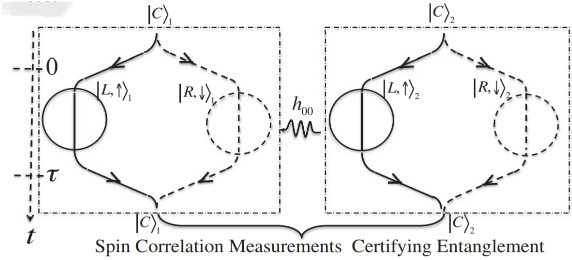
$\frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$

Gravitational Entanglement Witnessing in Complete Stern Gerlach Interferometry



- Step 1: Spin dependent spatial splitting of the center of mass state: $|C\rangle_j \; \frac{1}{\sqrt{2}}(|\uparrow\rangle_j + |\downarrow\rangle_j) \rightarrow \frac{1}{\sqrt{2}}(|L,\uparrow\rangle_j + |R,\downarrow\rangle_j)$.
- Step 2: "Holding" the superposition for a time τ – magnetic field switched off.
- Step 3: Bringing back the spatial superposition: $|L,\uparrow\rangle_j \rightarrow |C,\uparrow\rangle_j$; $|R,\downarrow\rangle_j \rightarrow |C,\downarrow\rangle_j$.

Gravitational Entanglement Witnessing in Complete Stern Gerlach Interferometry



If gravity is quantum $\Rightarrow$ Entangled state of the spins of the two test masses:

$$|\Psi\rangle_{12} = \left(|\uparrow\rangle_1 \frac{1}{\sqrt{2}} \left(|\uparrow\rangle_2 + e^{i\Delta\phi_{LR}} |\downarrow\rangle_2 \right) + |\downarrow\rangle_1 \frac{1}{\sqrt{2}} \left(e^{i\Delta\phi_{RL}} |\uparrow\rangle_2 + |\downarrow\rangle_2 \right) \right) |C\rangle_1 |C\rangle_2$$

– can be verified by measuring the **spin correlations**.

E.g. $W = \left| \langle \sigma_x^{(1)} \otimes \sigma_x^{(1)} \rangle + \langle \sigma_y^{(1)} \otimes \sigma_y^{(1)} \rangle \right|$: If $W > 1$, the state is entangled.

Ensuring Gravitational Interaction to be Dominant

- One can cancel all but one (Casimir-Polder) of the electromagnetic interactions[6].
- Aim: Getting to get enough detectable entanglement[7] $\equiv$
$$\Delta\phi_{LR} + \Delta\phi_{RL} = \frac{Gm_1 m_2 \tau}{\hbar}\left(\frac{1}{d-\Delta x} + \frac{1}{d+\Delta x} - \frac{2}{d}\right) \sim 1.$$
- $(d - \Delta x)$ can be large at the expense of large m_1 and m_2 – Very difficult to prepare spatial superposition of large masses.
- m_1 and m_2 can be made smaller at the expense of small $(d - \Delta x)$ – If $(d - \Delta x)$ is too small, Casimir-Polder will be dominant compared to Gravitational interaction!!!

[6] *See* **PRL 119, 240401** *for the techniques to neutralize the masses, as well as to get rid of the charge multipole-charge multipole interactions, while the direct magnetic dipole interaction between the two spins is truly negligible in comparison to gravity at the relevant distances.*

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

- Gravitational potential will be at least one order of magnitude larger than the Casimir-Polder potential, if[8]

$$d - \Delta x \gtrsim 157\mu\text{m}$$

(considering the system to be diamond with one NV center point, where the electronic spin can be embedded).

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

- Practical Parameter Regime[9]: $m_1,\ m_2 \sim 10^{-14}$ kg,
  $d - \Delta x \sim 200\mu\text{m}\ (\frac{U_{\text{Casimir}}}{U_{\text{Gravity}}} \sim \frac{1}{10})$,
  $\tau \sim 1$ s,
  $\Delta x \sim 100\mu\text{m}$.

$\Rightarrow$ Enough Detectable Entanglement $(\Delta\phi_{LR} + \Delta\phi_{RL} \sim 1)$.

[9] Schut, Geraci, Bose, Mazumdar, Phys. Rev. Research **6**, 013199 (2024).

- If decoherence rate $\Gamma >$ certain threshold ($\frac{d\overline{\Delta\phi}}{dt}$ with $\overline{\Delta\phi} = \frac{\Delta\phi_{LR}+\Delta\phi_{RL}}{2}$), no entanglement is generated.

  $\Rightarrow$ The protocol fails.[10]

- For such high decoherence rate, the coherence in the spatial superposition is not completely lost.

Can this remaining coherence be exploited to observe some nonclassicality of gravity (even if $\Gamma > \frac{d\overline{\Delta\phi}}{dt}$)?.

[10] Schut, Tilly, Marshman, Bose, Mazumdar, Phys. Rev. A **105**, 032411 (2022); Rijavec, Carlesso, Bassi, Vedral, Marletto, New Journal of Physics **23**, 043040 (2021).

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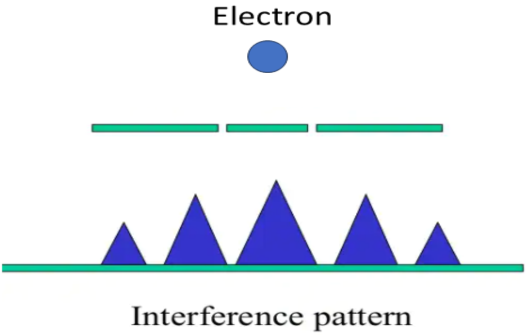
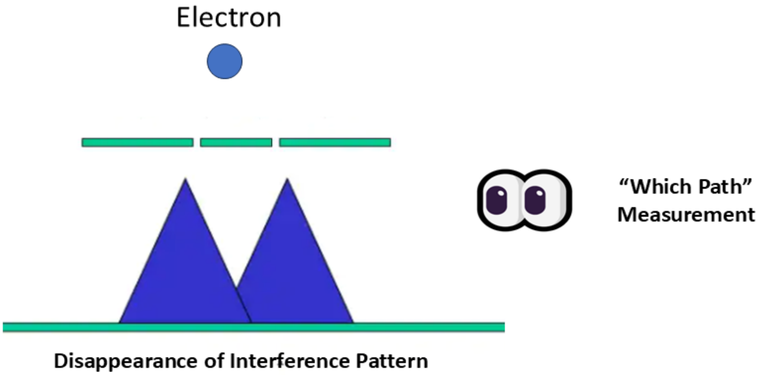
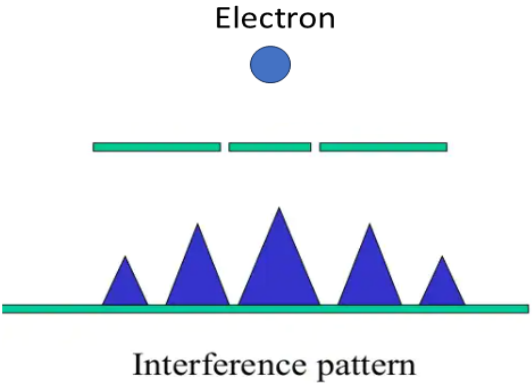
Double-Slit Experiment with Electrons



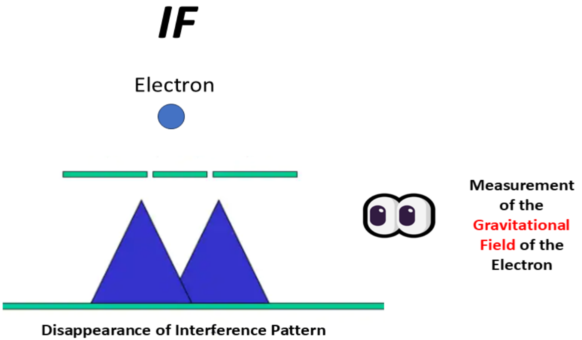


- Due to Quantum Measurement Induced Disturbance.

Part I of the Expt.:



Part II of the Expt.:



⇒ **Gravity is non-classical**

- NDC violation persists for any finite decoherence rate.

  $\Rightarrow$ Unlike the "2017 proposals".

  With an increase in decoherence rate, the magnitude of NDC violation decreases – Can be offset by increasing the number of runs.

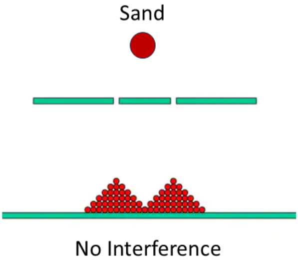
- Does not require trusted measurement devices.

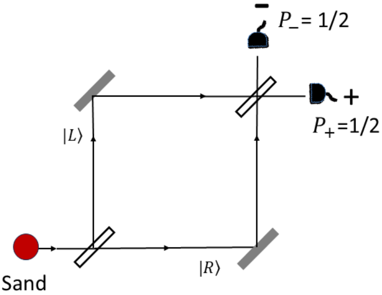
  $\Rightarrow$ Unlike the "2017 proposals".

- Entanglement generation between the source mass and the probe mass is not necessary.

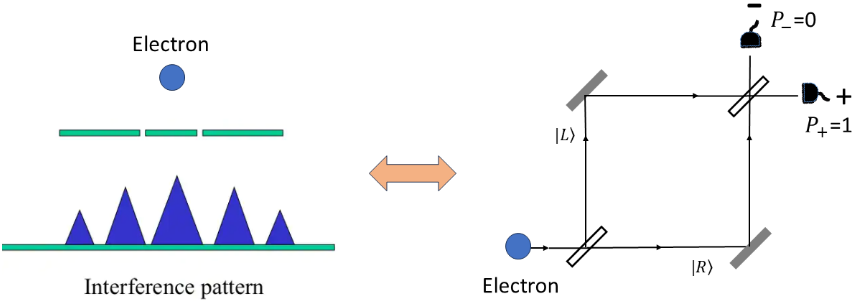
  $\Rightarrow$ Independent from the "2017 proposals".

Mach-Zehnder interferometer





Mach-Zehnder interferometer



Parameter Regime

Taking M, $m \sim 10^{-14}$ kg, $d \sim 157\mu$m (ensures $\frac{U_{\text{Casimir}}}{U_{\text{Gravity}}} \sim \frac{1}{10}$)