The search for a table top quantum gravity signature

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1957

***The Role of Gravitation in Physics. Report from the 1957 Chapel Hill Conference*. D. Rickles and C. DeWitt. (Max Planck Institute for the History of Science eds.)**

Richard Feynman: “We’re in trouble if we believe in quantum mechanics but don’t quantize gravitational theory ”

Richard Feynman: “One should think about designing an experiment which uses a gravitational link and at the same time shows quantum interference”

Louis Witten: “What prevents this from becoming a practical experiment?”.

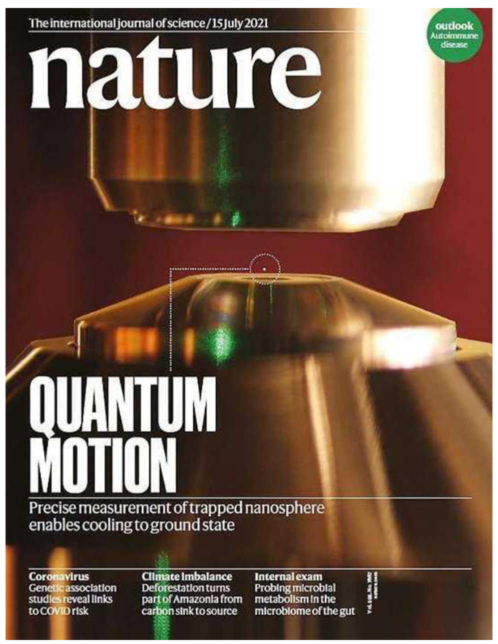
Richard Feynman: “You might argue this way: Somewhere in your apparatus this idea of [probability] amplitude has been lost. You don’t need it any more, so you drop it. The wave packet would be reduced (or something). Even though you don’t know where it’s reduced, it’s reduced. And then you can’t do an experiment which distinguishes interfering alternatives from just plain odds (like with dice).”

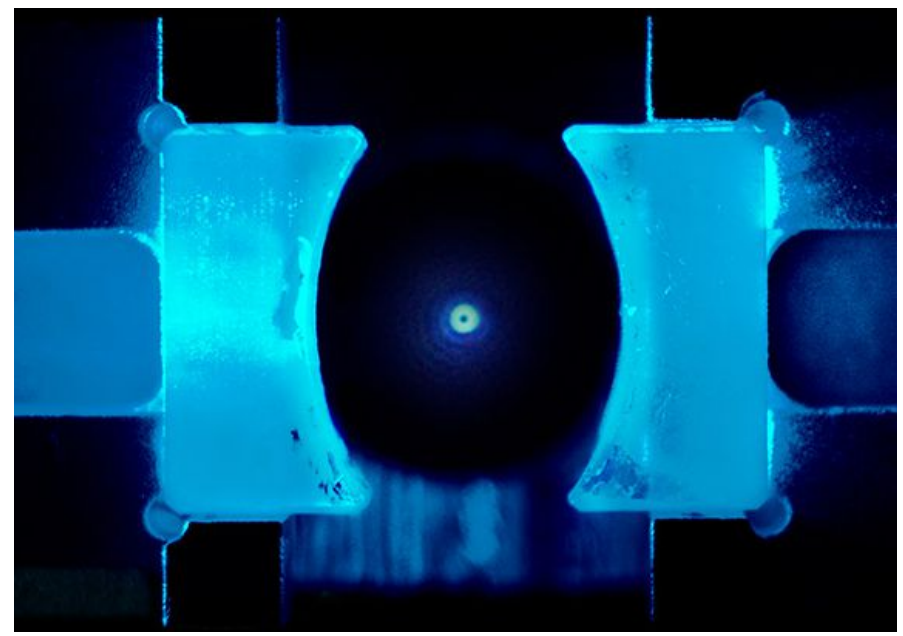
In modern parlance, entanglement through the gravitational interaction seems to imply a quantised gravitational field. The main trouble from realising such an experiment is decoherence to the environment which implies that the outcomes of measurements on the probe will be described by a probabilistic mixture. Sixty three years later, we may realistically hope to see this experiment done within a generation.

***How to avoid the appearance of a classical world in gravity experiments*. M. Aspelmeyer (2203.05587)**

Macroscopic Quantum Mechanics in the lab

Using quantum levitation combined with optical cooling ground state preparation of particles at 10^-18kg (10^9 atoms) have been reported. Claims that several orders of magnitude improvement can happen within a couple of years, going up to 10^-12kg (10^15 atoms).



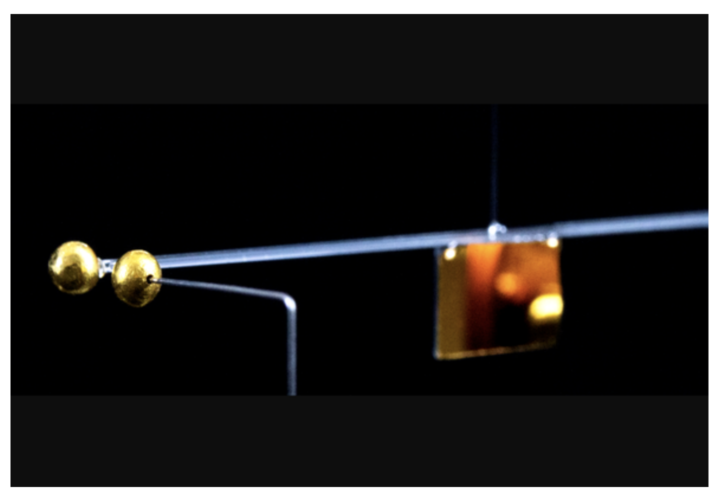


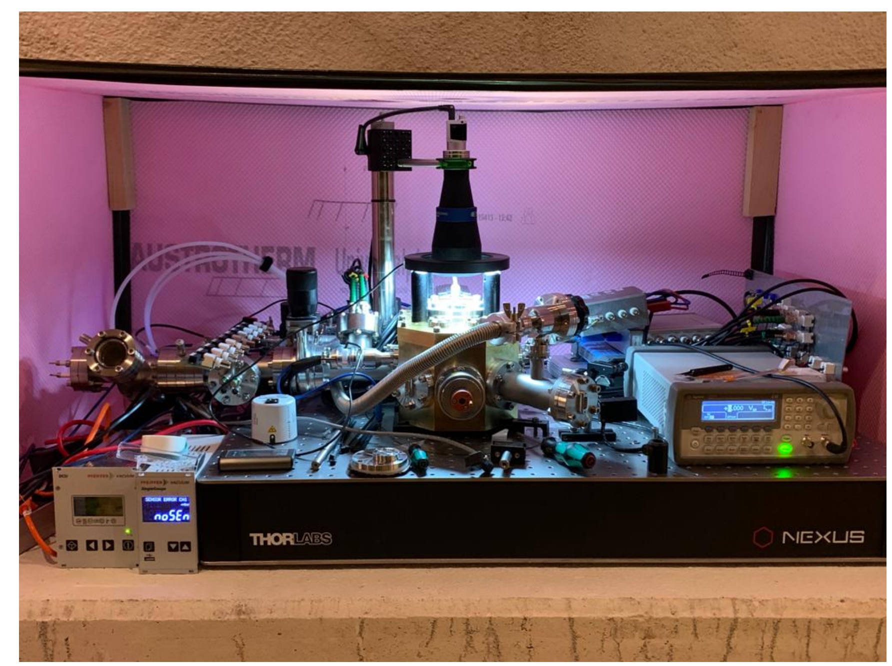
Real-time optimal quantum control of mechanical motion at room temperature, L. Magrini, P. Rosenzweig, C. Bach, A. Deutschmann-Olek, S. Hofer, S. Hong, N. Kiesel, A. Kugi and Markus Aspelmeyer (Nature 2021)

Quantum control of a nanoparticle optically levitated in cryogenic free space, F. Tebben, M. Mattana, M. Rossi, M. Frimmer, and L. Novotny (Nature 2021)

Precision gravity measurements

Gravitational force between masses of 10^-5kg measured. Claimed that soon 10^-8kg (planck mass) or below.

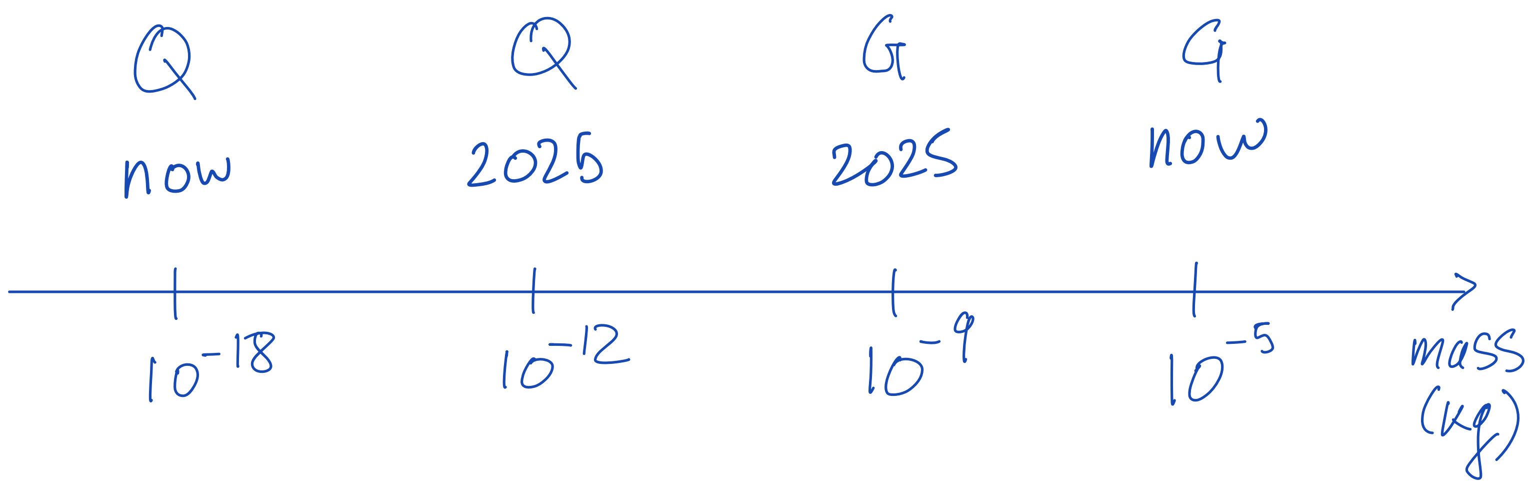




Measurement of gravitational coupling between millimetre sized masses, T. Westphal, H. Hepach, J. Pfaff, M. Aspelmeyer (Nature 2021)

Physicists Measure the Gravitational Force between the Smallest Masses Yet, SA

Summary of experimental news



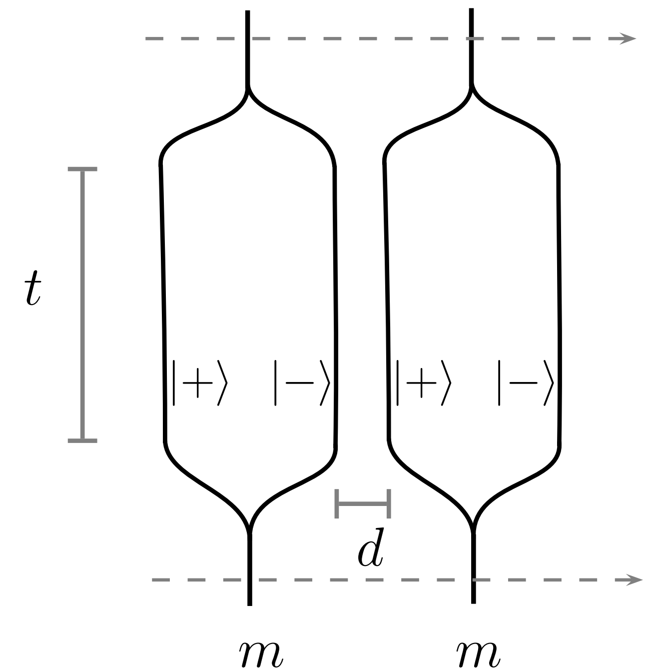
Overlap of mass scales should come soon, which will be an exciting moment. This overlap, however, in the limited sense that collective degrees of freedom (typically center of mass) of mesoscopic masses can be both set in their ground state and their gravitational field measured at the same scale.

Many great experimental challenges ahead:

- **Create coherent superposition, not just ground state preparation.**
- **Keeping coherence long enough**
- **Combine the two: Q + G in one experiment.**
- **What is the most feasible setup/protocol?**

How to avoid the appearance of a classical world in gravity experiments. M. Aspelmeyer (2203.05587)

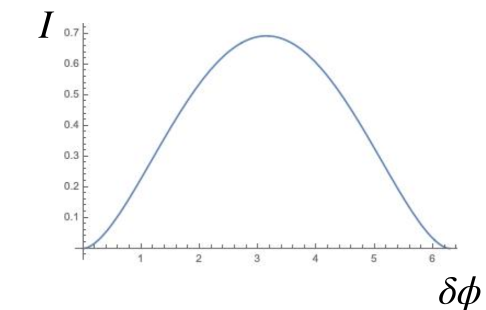
One simple setup for gravity induced entanglement



$$|\Psi_f\rangle \propto \left(|{+}{+}\rangle + |{-}{-}\rangle + |{+}{-}\rangle + e^{i\delta\phi(m,d,t)}\,|{-}{+}\rangle\right) \otimes |g\rangle$$

If the phase δϕ is not zero then there is entanglement production.

Entanglement entropy



$$|\Psi_i\rangle = |\psi_A\rangle \otimes |\psi_B\rangle \otimes |g\rangle$$
$$\propto \left(|{+}{+}\rangle + |{-}{-}\rangle + |{+}{-}\rangle + |{-}{+}\rangle\right) \otimes |g\rangle$$

Each mass prepared initially in a separable state

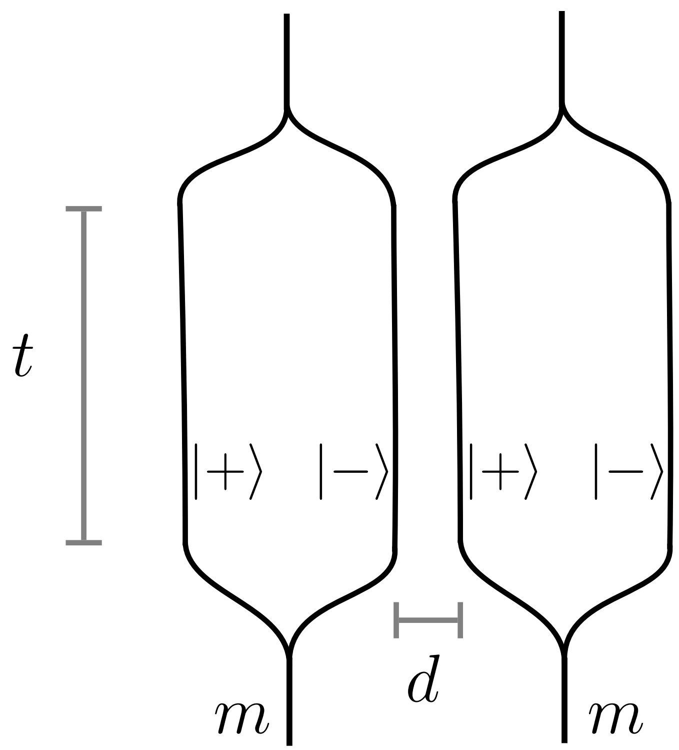
$$|\psi_{AB}\rangle = |\psi_A\rangle \otimes |\psi_B\rangle = (|+\rangle + |-\rangle) \otimes (|+\rangle + |-\rangle)$$

Spin entanglement witness for quantum gravity. **S. Bose, A. Mazumdar, G. Morley, H. Ulbricht, M. Toroš, M. Paternostro, A. Geraci, P. Barker, M. Kim, G. Milburn (1707.06050)**

Gravitationally induced entanglement between two massive particles is sufficient evidence of quantum effects in gravity, **C. Marletto and V. Vedral (1707.06036)**

Observable quantum entanglement due to gravity, **T. Krisnanda, G. Y. Tham, M. Paternostro, T. Paterek (1906.08808)**

Newtonian gravity suffices for numerical evaluation of entanglement



Newtonian potential energy

$$E_g = \frac{Gm^2}{d}$$

Free evolution

$$e^{i\delta\phi} = e^{i\frac{E_g t}{\hbar}}$$

Quantum phase

$$\delta\phi = \frac{Gm^2 t}{d\,\hbar}$$

These formulas determine the basic parameters m,t,d at which the experiment would need to operate . **There is nothing to be concluded from these formulas about QG.**

Assuming a local interaction, if entanglement is detected, then, the argument goes, we must conclude that the gravitational field cannot be a classical field.

The `trick' is to force one to either conclude this or abandon locality.

The question becomes, how do we describe this local mediation concretely in the framework of well studied theories like, QED and effective low energy QG? Surprisingly, this is not obvious.

Overview of debate on relevance of GIE for QG

The two extremes

GIE nothing to do with QG

(even assuming locality, the `true' degrees of freedom do not participate, no mediation)

Comment on Bose et al and Marletto-Vedral papers. **C. Anastopoulos, B. Hu (1804.11315)**

'We argue that gravity-induced entanglement by Newtonian forces is **agnostic to the quantum or classical nature** of the gravitational true degrees of freedom.'

Gravitational effects in macroscopic quantum systems: a first principles analysis. **C. Anastopoulos, M. Lagouvardos, K. Savvidou (1804.11315)**

'We analyze phenomena like gravity-induced entanglement.. Our main results include: (i) The demonstration that these phenomena **do not involve true gravitational degrees of freedom**...'

GIE implies detection of virtual gravitons

(entanglement just Newtonian interaction law but this is mediation because it is exchange of virtual gravitons)

Locality & Entanglement in Table-Top Testing of the Quantum Nature of Linearized Gravity. **R. Marshman, A. Mazumdar, S. Bose (1907.01568)**

'We explain the background concepts needed from quantum field theory and quantum information theory to fully appreciate the previously proposed table-top experiments: namely **forces arising through the exchange of virtual (off-shell) quanta**, as well as Local Operations and Classical Communication (LOCC) and entanglement witnesses'

Mechanism for the quantum natured gravitons to entangle masses. **S. Bose, A. Mazumdar, M. Schut, M. Toros (2201.03583)**

'We will use basic quantum mechanics and perturbation theory to show how the perturbed wave functions of **the matter systems become entangled solely by the virtue of the virtual exchange** of the quantum natured graviton.'

Overview of debate on relevance of GIE for QG

Some middle grounds

GIE implies quantum information carried by `non radiative' part

(if the mediator is `usual radiation' the effect should not take place because we would lose interference. So what is it?)

Experiments testing macroscopic quantum superpositions must be slow. **A. Mari, G. De Palma and V. Giovannetti. (1509.02408)**

Quantum superposition of massive objects and the quantisation of gravity. **A. Belenchia, B. Wald, F. Giacomini, E. Castro-Ruiz, C. Brukner, M. Aspelmeyer (1807.07015)**

Information content of the gravitational field of a Quantum superposition. **A. Belenchia, R. Wald, F. Giacomini, E. Castro-Ruiz, C. Brukner, M. Aspelmeyer (1905.04496)**

'Thus, a Newtonian-like gravitational field must be capable of carrying quantum information… Since there is no radiation, **it clearly must be the "non-radiative part" of the electromagnetic/gravitational field that is responsible for the ultimate entanglemen**t of Alice's and Bob's particles.'

GIE implies detection of on-shell gravitons

(still, it should be in some sense gravitons mediating because what else?)

Newton, entanglement and the graviton. **D. Carney. (2108.06320)**

'I demonstrate that this **"Newtonian entanglement" requires the existence of massless bosons**…'

Gravitationally Mediated Entanglement: Newtonian Field vs. Gravitons, **D. Danielson, G. Satishchandran and R. Wald. (2112.10798)**

'…the experimental discovery of **Newtonian entanglement may be viewed as implying the existence of the graviton.**'

Overview of debate on relevance of GIE for QG

‘Our’ middle ground

GIE implies detection of macroscopic superposition of spacetimes

On the possibility of laboratory evidence for quantum superposition of geometries. M. Christodoulou, C. Rovelli (1804.11315)

‘We point out that measurement of **this effect would count as evidence for quantum superposition of spacetime geometries.**’

Locally mediated entanglement from first principles. M. Christodoulou, A. Di Biagio, M. Aspelmeyer, C. Brukner, C. Rovelli, R. Howl (2202.03368)

‘The physical picture arising from the analysis is that information travels in the quantum superposition of field wavefronts: **the mechanism that propagates the quantum information with the speed of light is a quantum superposition of macroscopically distinct dynamical field configurations.**’

Photonic Implementation of Quantum Gravity Simulator. E. Polino … F. Sciarrino, C.Rovelli, A. Di Biagio, M. Christodoulou (2207.01680)

‘In the gravitational experiment, **the states of the geometry should acquire which-path information about the masses, but they should not propagate that information to infinity.**’

Gravity entanglement, quantum reference frames, degrees of freedom. M. Christodoulou, A. Di Biagio, R. Howl, C. Rovelli (2207.03138)

‘Physically, precisely because matter is quantum so is the longitudinal field: **as matter can be in quantum superposition, so can the longitudinal field.**’

The confusion is related to the existence of different notions of transversality

On a basic conceptual confusion in gravitational radiation theory. A. Ashtekar, B. Bonga. (1707.07729)

On the ambiguity in the notion of transverse traceless modes of gravitational waves. A. Ashtekar, B. Bonga. (1707.09914)

Further references

For other recent summaries of (aspects of) the debate see:

Quantum Gravity in a laboratory? **N. Huggett, N. Linnemann, M. Schneider (2205.09013)**

On inference of quantisation from gravitationally induced entanglement. V. Fragkos, M. Kopp, I. Pikovski (2206.00558)

Complementarity and causal propagation of decoherence by measurement in relativistic quantum field theories. **Y. Hidaka, S. Isho, K. Shimada (2205.08403)**

I have not discussed:

- The controversy regarding the extend to which a theory independent conclusion (à la Bell test) may be drawn from such experiments (applicability of LOCC theorems), see for instance:

A no-go theorem on the nature of the gravitational field beyond quantum theory. T. Galley, F. Giacomini, J. Selby **(2012.01441)**

Vindication of entanglement based witness of non classicality of hybrid systems. E. Marconato, C. Marletto **(2102.10615)**

- Related alternative protocols and effects, see for instance:

On the possibility of experimental detection of the discreteness of time. **M. Christodoulou and C. Rovelli (1812.01542)**

An experiment to test the discreteness of time. M. Christodoulou, A. Di Biagio, P. Martin-Dussaud **(2007.08431)**

Non-gaussianity as a signature of a quantum theory of gravity. **R. Howl, V. Vedral, D. Naik, M. Christodoulou, C. Rovelli and A. Iyer. (2004.01189)**

Enhancing Gravitational Interaction between Quantum Systems by a Massive Mediator. **J. Pedernales, K, Streltsov, M. Plenio. (2104.14524)**