Tests of Quantum Gravity near Measurement Events

Adrian Kent

Centre for Quantum Information and Foundations, DAMTP,
Centre for Mathematical Sciences, University of Cambridge,
Wilberforce Road, Cambridge, CB3 0WA, United Kingdom and
Perimeter Institute for Theoretical Physics, 31 Caroline Street North, Waterloo, ON N2L 2Y5, Canada.

Experiments have recently been proposed testing whether quantum gravitational interactions generate entanglement between adjacent masses in position superposition states. We propose potentially less challenging experiments that test quantum gravity against theories with classical spacetimes.

INTRODUCTION

We have essentially no empirical evidence for quantum gravity, nor a complete theory, or a full conceptual understanding of what one would mean. It has been claimed that there is no logical alternative to quantizing gravity [1], but these arguments have been refuted [2–5]. An alternative idea is to look for a theory somehow unifying a (quasi-)classical description of spacetime and quantum matter. Again, no complete theory of this type is known. As yet, there is essentially no clear empirical evidence in either direction.

Quantum experiments with macroscopically amplified unpredictable outcomes seem a promising arena for possible new tests of quantum gravity. Consider, for example, a diagonally polarised photon whose polarization is measured in the horizontal-vertical basis, with the outcome generating a weak electrical pulse that, in one case, passes through a piezocrystal fixed at one end, causing it to deform. Suppose that the undeformed and deformed states of the piezocrystal plus cap have measurably distinct gravitational potentials, \( V_0 \) and \( V_1 \).

Perturbatively quantized general relativity (see e.g. [6]) predicts that, just after the experiment, any possible gravitational experiment will measure the field to be \( V_a \), where \( a \) labels the outcome. That is, we see the field \( V_0 \) or the field \( V_1 \), each with probability \( 0.5 \).

No fully classical model based on the principles of general relativity – specifically, on deterministic equations – can reproduce this prediction. If \( G_{\mu\nu} \) and \( T_{\mu\nu} \) have classical values and follow a deterministic evolution law their values just before the experiment determine their values just after, even if we assign non-standard classical values and a deterministic law other than the Einstein equations. It is logically possible that one outcome or the other could be modelled by GR (or by any given deterministic classical alternative), but not both.

Page and Geilker [7] carried out a larger scale version of this experiment and (controversially [8–10]) argued that the outcome gave indirect evidence for quantum gravity. One issue with this is that, for an experiment to have given evidence for quantum gravity, it must have diminished credence in at least one alternative, which means that alternative must previously have had some credence. The alternative Page-Geilker considered was Everettian semi-classical gravity [11, 12], in which

\[
G_{\mu\nu} = \langle \hat{T}_{\mu\nu} \rangle ,
\]

(1)

where the expectation value is defined by an Everettian universal wave function. The problem is that this was arguably already incredible. A cosmological model defined by [1] seems certain to be inconsistent with observation, since the universal wave function presumably contains components corresponding to a very large number of mass distributions, almost all of which are very different from the one we observe, and yet we see gravitational fields corresponding to the observed distribution. Nonetheless, Page and Geilker appear to have assigned nonzero credence to the possibility that an Everettian semi-classical gravity cosmological model could be consistent with observation, prior to their experiment. Another issue is that it is unclear whether there is even a self-consistent formulation of Everettian semi-classical gravity [13–18], although some credence in this may still be reasonable.

A more general alternative hypothesis to quantized gravity is that space-time remains classical in the neighbourhood of unpredictable quantum events, or at least that a classical model of space-time gives a good description of local experiments. If so, this cannot be by the standard Einstein equations nor by full Everettian semi-classical gravity, as just discussed. However it might, for example, be described by [1] with the expectation value taken with respect to some suitable quantum state that changes stochastically over time, for example via a dynamical collapse model [19–21]. Useful collapse models have to produce collapse within human perception times [20, 22–24]. The Page-Geilker experiment, which estimated the resulting gravitational fields from measurements carried out during the subsequent hour, excluded only very gross and long-lasting (hypothetical) collapse-induced effects. It also involved...
direct human intervention, with an observer moving lumps of matter to locations depending on the outcome of a quantum experiment, ensuring collapse by this point in any useful collapse model.

A classical space-time might alternatively be determined by other presently unknown rules. Although underspecified, this more general hypothesis surely currently deserves some credence: it is hard to argue that, even though we have no complete quantum theory of gravity, we need no experimental evidence to be certain nature must be described by one.

These possibilities motivate experiments on much smaller space and time scales than Page and Geilker’s. If space-time remains classical throughout, an unpredictable quantum event must apply a sort of localised “shock”. The Einstein equations presumably nonetheless apply to very good approximation soon after, since measurement-like interactions are ubiquitous in nature and Newtonian gravity and general relativity are very well tested. Perhaps the shock only creates a near-pointlike and presently undetectable “glitch”. However it seems worth searching for detectable effects in the neighbourhood of quantum measurement events, since all we can be certain of is that if gravity isn’t quantised then something presently unknown must happen there.

**SEMI-CLASSICAL GRAVITY**

We will discuss experimental tests of quantum gravity against the alternative of (1), suitably interpreted, in order to be specific, without excluding other possibilities. Arguably, even if other classical equations hold, (1) gives some rough upper estimate of the scale of any likely deviations from quantum gravity predictions. Roughly speaking, quantum gravity suggests that if we try to create a superposition of mesoscopically distinct mass distributions and measure the gravitational field we see the field associated with one component (chosen via the Born rule), while semi-classical gravity suggests that so long as the superposition is maintained we should see the weighted average of the fields. One can motivate something inbetween, for example as the weighted average of an incompletely collapsed state, but it seems hard to motivate equations that give larger deviations.

That said, (1) is not presently satisfactorily justified theoretically [6, 25, 26]. As Carney et al. [6] discuss in a very thoughtful recent review, some options can be identified in the non-relativistic limit with $N$ fixed particles, with mass density operator

$$\hat{M}(x) = \sum_i m_i \delta(x - \hat{x}_i),$$

and classical Newtonian potential $\Phi$ obeying

$$\nabla^2 \Phi(x) = 4\pi G \langle \hat{M}(x) \rangle.$$

This gives a modified Schrödinger equation

$$i \frac{\partial}{\partial t} |\psi\rangle = (\hat{H}_{\text{matter}} + \hat{H}_{\text{gravity}})|\psi\rangle = (\hat{H}_{\text{matter}} + \int \hat{M}(x) \Phi(x) dx)|\psi\rangle.$$

To avoid some of the issues arising from nonlinearity, they suggest considering this as a sort of flawed limit of a consistent non-relativistic quantum model, with an ancilla coupled to the quantum matter weakly monitoring its stress-energy and classically feeding back the associated Newtonian potential to define $\hat{H}_{\text{gravity}}$. They note that it may be challenging to find a relativistic version of this model.

Another line of thought is to consider semi-classical gravity in the context of some (not necessarily specified) localised collapse model [21, 27]. In this setting we propose to interpret $\langle \hat{T}_{\mu\nu}(x) \rangle$ as the expectation value associated with the local quantum state, defined by the local density matrix of the state at $x$ associated with collapses (only) in the past light cone $\Lambda_x$. [5, 27] This semi-relativistic prescription avoids the pathological superluminal signalling that arises from naively combining (1) and objective collapse or projective measurement. For the effects of collapses to propagate at light speed seems a plausible ansatz for the behaviour of (otherwise) non-relativistic systems obeying (4), although again it is unclear that it extends to a fully consistent relativistic theory. Models of this type have previously been used to motivate experiments testing other aspects of the relationship between quantum theory and gravity (e.g. [29, 30]).

For the right hand side of (1) ever to be a non-trivial expectation value, some non-trivial superpositions of significantly distinct mass distributions must sometimes persist for some while. The alternative is essentially Penrose’s gravitationally induced collapse hypothesis [31]: objective collapse of these matter states always suppresses superpositions so swiftly that (1) would never show any superposition effects. This appears to have recently been refuted by a
recent experimental analysis [32], which concludes that “the idea of gravity-related wave function collapse .. remains very appealing” but “will probably require a radically new approach”. Any such approach may necessarily have to allow superpositions of significantly distinct mass distributions to persist for significantly longer than Penrose’s [31] and Diosi’s [33] original estimates, while still ensuring that macroscopic superpositions collapse. Equation (1) seems a natural way of avoiding quantum superpositions of distinguishable spacetimes in such a theory, with a collapse criterion weaker than Penrose-Diosi’s but not so weak that macroscopic superpositions persist in the Page-Geilik experiment.

In summary, there are a variety of reasons for considering (1,4). None of the relevant lines of thought is presently known to lead to a complete consistent relativistic theory. But since this is also true of all approaches to quantum gravity, we still see motivation for viewing (1,4) as possible effective models in limited domains, worth testing in suitable experiments.

EXPERIMENTAL TESTS

Consider two small spheres $S_i$ ($i = 1, 2$) of radius $r_i$ and mass $m_i$. For simplicity, we take them to be of the same material of density $\rho$, so that $m_i = \frac{4}{3}\pi(r_i)^3\rho$. We will be particularly interested in the case $m_1 \geq m_2$.

The setup includes apparatus for preparing a quantum system and then making a measurement with two equiprobable results ($R_0$ and $R_1$). For example, a diagonally polarized photon could be emitted by a single photon source and measured in the horizontal-vertical polarization basis. For the moment we consider the ideal case, with a perfect source, no noise or losses and perfectly efficient detector, so that the experiment always produces a definite outcome. For result $R_0$, no pulse is produced and $S_1$ is held at its initial position. For result $R_1$, the experiment produces a small electrical pulse in a circuit that controls the release of sphere $S_1$, with the pulse releasing $S_1$ to freely fall under gravity. The release mechanism should be as microscopic as possible, in the sense that the gravitational fields associated with the mechanism state of release and no release differ by as little as possible, and in particular by significantly less than the gravitational fields associated with $S_1$ in the two states (held and released). A circuit switching a laser or magnetic field on or off, while causing essentially no displacement of anything other than $S_1$, might be a suitable choice.

Adjacent to the free fall path of $S_1$, we place a Stern-Gerlach interferometer for $S_2$, of the type discussed in Ref. [34]. This allows $S_2$ to fall freely for some distance $h$ and then to enter a superposition of two equal length spin-dependent paths (L and R) that later recombine. In every run of the experiment, $S_2$ is released at the top of the interferometer and its final state after the experiment is measured when the position degrees of freedom have been recombined, leaving the gravitational field dependent phase encoded in the spin degree of freedom. The two parts of the experiment are synchronized so that, if $S_1$ is released in a given run, it and $S_2$ will be released and fall together. To simplify, we take $h$ large enough that the Newtonian potential between $S_1$, in its initial position, and $S_2$, within the two-path part of the interferometer, is negligible: if not, its effects can be calibrated along with those of other gravitational potentials.

Let $t$ be the length of time during which $S_2$ falls through the part of the interferometer where the paths are maximally separated, and $T$ the time between the start of the experimental run and the end of this part of $S_2$’s fall; let the times taken to fall through the parts where the paths are separating and recombining be $\approx \delta t$, with $t \gg \delta t$. Let $x_1, x_2$ be the separations between the path of $S_1$ (if released) and the two paths of $S_2$ at maximal separation, with $x_1 < x_2$. (See Fig. 1.)

First we give an analysis based on perturbatively quantized general relativity. This treats separately the cases where $S_1$ is released or held, and takes the combined system to follow the Schrödinger equation with a Newtonian potential between $S_1$ and $S_2$. For now we neglect gravitational potentials due to other bodies and other interactions.

We assume that the outcome of the quantum experiment, and so the final state of $S_1$ (held or released), are determined by some appropriate measurement well after time $T$. This measurement outcome is used to infer what happened to $S_1$ during the experiment, in the sense generally used in discussing binary quantum trajectories associated with different measurement outcomes. In this sense we can say that “$S_1$ was held” or “$S_1$ was released”, without any necessary commitment to a particular interpretation of the reality or otherwise of quantum histories. Similarly we use “$S_1$ is held” as shorthand for “a future measurement will give outcome corresponding to the history in which $S_1$ remains in situ”, and “$S_1$ is released” as shorthand for the future measurement giving the outcome corresponding to the alternative history in which $S_1$ falls freely during the experiment.

If $S_1$ is held, and $S_2$ enters the two-path part of the interferometer in state $\frac{1}{\sqrt{2}}(|L\rangle + |R\rangle)$, there is no potential
FIG. 1: Schematic description of experiment (not to scale). An indeterministic quantum measurement outcome is relayed by a small electrical pulse to an apparatus that (for example by switching a magnetic field) either holds or releases the sphere $S_1$ at time $t = 0$. At the same time, $S_2$ is released, falling under gravity through a Stern-Gerlach interferometer. Distances are represented by orange arrows, times of fall by green arrows. Paths with amplitude 1 are represented by solid blue lines; paths with smaller amplitudes by dotted blue lines.

The difference between the two paths and its state after time $t$ is

$$|\psi(t)\rangle \approx \frac{1}{\sqrt{2}}(|L\rangle + |R\rangle).$$  \hfill (5)

If $S_1$ is released, it falls alongside $S_2$, closer to one path than the other.

$$|\psi(t)\rangle \approx \frac{1}{\sqrt{2}} \exp(i\phi_L t)\left(|L\rangle + \exp(i(\phi_R - \phi_L)t)|R\rangle\right),$$  \hfill (6)

where

$$\phi_L = \frac{Gm_1m_2}{\hbar x_1}, \quad \phi_R = \frac{Gm_1m_2}{\hbar x_2}. \hfill (7)$$

Alternatively, on a semi-classical gravity analysis, assuming no collapse affects $S_1$ until after time $T$, the gravitational potentials take the same value $\frac{1}{2} \frac{Gm_1m_2}{x}$ whether $S_1$ is held or dropped. We have

$$|\psi(t)\rangle \approx \frac{1}{\sqrt{2}} \exp(i\phi_L t/2)\left(|L\rangle + \exp(i(\phi_R - \phi_L)t/2)|R\rangle\right),$$  \hfill (8)

If

$$(\phi_R - \phi_L)t \approx 1,$$  \hfill (9)

or more generally if $(\phi_R - \phi_L)t \mod 2\pi$ is significantly nonzero, we can distinguish (5), (6) and (8). For example, in principle a measurement in the basis $(|L\rangle \pm |R\rangle)$ gives different outcome frequencies in the three cases.

Consider now an alternative version of the experiment in which there is no initial quantum measurement, and $S_1$ is always held at its initial location. In this case, both quantum gravity and semi-classical gravity make the same prediction (5). Comparing the results of this experiment with those of the subensemble of the quantum experiment in which $S_1$ is not released thus suffices to test between the two hypotheses.

This has significant practical advantages. First, a more realistic analysis needs to allow for the likelihood that the paths are not quite equal length, and for the phase effects of gravitational potentials from the Earth and from nearby objects. These effects are identical in both versions of the experiment, so that the deterministic version can be used to calibrate the quantum version. It needs also to allow for the gravitational self-interaction predicted by semi-classical gravity for $S_2$. This too should be near-identical in both versions of the experiment, since the displacement of $S_2$ caused by gravitational interaction with $S_1$ is negligible.

Second, when $S_1$ is not released, then so long as the initial locations of $S_1$ and $S_2$ are chosen so that their Casimir-Polder (CP) interactions [35, 36] are negligible, the CP interactions can be neglected throughout any run
of the experiment (in either version) in which $S_1$ is not released. These interactions are governed by quantum electrodynamics, not by a semi-classical theory. A significant interaction in the case where $S_1$ is released is thus irrelevant to the cases where it is not. This means that the experiment can be set up so that (at least) one path of $S_2$ is very close to the path that $S_1$ follows if released, without needing to estimate the CP potential or ensure that it is smaller than the gravitational potential.

The latter is a significant difference compared to proposed experiments \cite{34 37} that test quantum gravity by testing whether entanglement is generated between small masses in two adjacent interferometers. In those experiments, the CP potentials must be significantly smaller than the gravitational potentials, to ensure that any entanglement generated must have been via the gravitational interaction. This gives a lower bound on the separation between interferometer paths, which implies challenging lower bounds on the masses.\cite{42} Our proposed experiment is also less constrained in that we are free to take $m_1 \gg m_2$, which allows \cite{9} to hold for smaller masses $m_2$ than those considered in Refs. \cite{34 37}. Both of these freedoms can be used to make the interferometry part of the experiment somewhat less challenging, by using a smaller mass $m_2$ and/or a shorter time $t$.

Bose et al. \cite{34} suggest spheres of radius $r = 10^{-8} \text{m}$ with masses $m_1 = m_2 = 10^{-14} \text{kg}$, and separations (in their case between the nearest path of $S_1$ to the paths of $S_2$) of $x_1 = 2 \times 10^{-4} \text{m}$, $x_2 = 7 \times 10^{-4} \text{m}$, with the paths adjacent for time $t = 2 \text{sec}$ for a two interferometer experiment that perturbatively quantized general relativity predicts should produce significant entanglement from gravitational interactions, with a relatively negligible contribution from Casimir-Polder interactions.

In the regime $x_1 \ll x_2$

$$\phi_L - \phi_R \approx \frac{Gm_1m_2t}{x_1^3 \hbar}.$$  

In our proposed experiment, in principle, we could retain the value of $m_1 \approx 10^{-14} \text{kg}$ and take $x_1$ significantly smaller, perhaps as far as $x_1 \approx 2 \times 10^{-6}$, allowing $m_2 t$ to be two orders of magnitude smaller. Alternatively, while keeping $x_1 \approx 2 \times 10^{-4} \text{m}$ and $x_2 \approx 7 \times 10^{-4} \text{m}$, the sphere $S_1$ could be made significantly larger and more massive. Taking $S_1$ of radius $\approx 10^{-4} \text{m}$ gives $m_1 = \frac{4}{3} \pi r_1^3 \approx 10^{-8} \text{kg}$, which would allow $m_2 t$ to be six orders of magnitude smaller.

Another option is to take $S_1$ larger still, with radius $r_1 \approx x_1$, where now $x_1 > 2 \times 10^{-4} \text{m}$, again with $m_1 = \frac{4}{3} \pi r_1^3$. This gives

$$\phi_L - \phi_R \approx \frac{Gm_2tx_1 \Delta x}{\hbar},$$

where $\Delta x$ is the maximum separation between paths in $S_2$’s interferometer. This allows $m_2 t \Delta x$ to be decreased proportionately to $x_1^{-1}$.

We should stress that the assumption that no collapse affects $S_1$ until after time $T$ is crucial and non-trivial. Its validity depends, among other things, on the interactions between $S_1$ and $S_2$ and between both systems and the environment, and on the details of the specific collapse model considered.

Precisely how far it is possible to exploit these various options in practice is a technological challenge that we propose for experimentalist colleagues.

**DISCUSSION**

The experiments we propose test quantum gravity against semi-classical gravity or some other quasi-classical theory on small scales, in the neighbourhood of a measurement-like quantum event, where any anomalous effects seem likeliest. Compared to the beautiful experiments discussed in Refs. \cite{34 37}, which also test quantum gravity against quasi-classical gravity models, they allow more freedom in the experimental parameters and so appear likely to be possible sooner. There is a persuasive case \cite{34 37 38} that those experiments should give a definitive signature, by generating witnessable entanglement if gravity does indeed involve the exchange of quantum states. This is not true of the experiments we propose: any evidence they give for quantum gravity would be more indirect, by reducing the credence in a still possible alternative. Although it is not immediately clear what specific credible alternatives other than some version of semi-classical gravity would be excluded by detecting entanglement in the experiments of Refs. \cite{34 37}, excluding a general class of theories is very valuable. We thus believe the motivation for these experiments would remain extremely compelling if our experiments showed no evidence for semi-classical gravity. Conversely, in our view, it would be worth continuing to carry out versions of our experiments across as wide a range of parameters as possible even if entanglement were detected in the experiments of Refs. \cite{34 37}. Although we are aware of no specific
credible proposal in this direction, one could perhaps imagine, for example, that gravity is mediated by quantum state exchange at scales sufficient to generate the predicted phases and entanglement in the experiments of Refs. but that some quasiclassical model of gravity nonetheless describes the gravitational field.

We have focussed on a specific example of a way of amplifying a quantum measurement-type event towards the mesoscopic, by dropping or releasing a small mass, depending on the outcome. The essential experimental concept applies to any amplification technique. For example, another possibility is to use the outcome to determine whether or not to pass a small current through a piezocrystal, which deforms in response, a technique used to probe the collapse locality loophole. As in Ref. the piezocrystal may be capped by a denser material; for suitable parameters the difference in gravitational fields may be dominated by the fields from the two locations of the cap, simplifying the analysis. This or other techniques may be more feasible in some regimes. In principle there are many other options (see e.g. for brief discussion). It is also possible to use a mechanical resonator in place of the interferometer. We leave for future work a systematic analysis of ways to stochastically alter gravitational fields, the speeds and magnitudes possible, and the feasibility of measuring the fields by sensitive nearby devices.

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* Electronic address: A.P.A.Kent@damtp.cam.ac.uk

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[42] Even for runs where $S_1$ is released, our experiment does not necessarily require the CP potential to be smaller than the gravitational potential, so long as the CP potential’s contribution to the overall phase can be precisely estimated.