Testing quantum gravity near measurement events

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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 defined by postulating semiclassical gravity (or classical effects of similar scale) for mesoscopic systems.

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I. INTRODUCTION

We have essentially no empirical evidence for quantum gravity, nor a complete theory, nor 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 polarized 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., Ref. [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 nonstandard classical values and a deterministic law other than the Einstein equations. It is logically possible that one outcome or the other could be modeled by GR (or by any given deterministic classical alternative), but not both. In fact, it seems unlikely that either outcome arises from any sensible deterministic model, since this would suggest some distinction between the outcomes that seems hard to align with our current understanding of physics.

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 semiclassical gravity [11,12], in which

$$G_{\mu\nu} = \langle \hat{T}_{\mu\nu} \rangle, \quad (1)$$

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 Eq. (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 semiclassical 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 semiclassical gravity [13–18], although some credence in this may still be reasonable.

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A more general alternative hypothesis to quantized gravity is that spacetime remains classical in the neighborhood of unpredictable quantum events, or at least that a classical model of spacetime gives a good description of local experiments. If so, this cannot be by the standard Einstein equations nor by full Everettian semiclassical gravity, as just discussed. However it might, for example, be described by Eq. (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 spacetime 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 spacetime remains classical throughout, an unpredictable quantum event must apply a sort of localized "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 neighborhood of quantum measurement events, since all we can be certain of is that if gravity is not quantized then *something* presently unknown must happen there.

II. SEMICLASSICAL GRAVITY

We will discuss experimental tests of quantum gravity against the alternative of Eq. (1), suitably interpreted, in order to be specific, without excluding other possibilities. Arguably, even if other classical equations hold, Eq. (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 semiclassical gravity suggests that so long as the superposition is maintained we should see the weighted average of the fields. One can motivate something in between, for example as the weighted average of an incompletely collapsed state, but it seems hard to motivate equations that give larger deviations.

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

$$\hat{M}(x) = \sum_i m_i \delta(x - \hat{x}_i), \tag{2}$$

and classical Newtonian potential Φ obeying

$$\nabla^2 \Phi(x) = 4\pi G \langle \hat{M}(x) \rangle. \tag{3}$$

This gives a modified Schrödinger equation

$$\begin{aligned} i\frac{\partial}{\partial t}|\psi\rangle &= (\hat{H}_{\mathrm{matter}} + \hat{H}_{\mathrm{gravity}})|\psi\rangle \\ &= \left(\hat{H}_{\mathrm{matter}} + \int \hat{M}(x)\Phi(x)dx\right)\middle|\psi\right\rangle. \end{aligned} \tag{4}$$

To avoid some of the issues arising from nonlinearity, they suggested considering this as a sort of flawed limit of a consistent nonrelativistic 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 $\hat{H}_{\mathrm{gravity}}$. They noted that it may be challenging to find a relativistic version of this model.

Another line of thought is to consider semiclassical gravity in the context of some (not necessarily specified) localized 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 Λ_x [5,27]. This semirelativistic prescription avoids the pathological superluminal signaling [28] that arises from naively combining Eq. (1) and objective collapse or projective measurement. For the effects of collapses to propagate at light speed seems a plausible ansatz for the behavior of (otherwise) nonrelativistic systems obeying Eq. (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., Refs. [29,30]).

For the right-hand side of Eq. (1) to ever be a nontrivial expectation value, some nontrivial superpositions of significantly distinct mass distributions must sometimes persist for some time. The alternative is essentially Penrose's gravitationally induced collapse hypothesis [31]: objective collapse of these matter states always suppresses superpositions so swiftly that Eq. (1) would never show any superposition effects. This appears to have recently been refuted by a recent experimental analysis [32], which concluded 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-Geilker experiment.

In summary, there are a variety of reasons for considering Eqs. (1) and (4). None of the relevant lines of thought are 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 Eqs. (1) and (4) as possible effective models in limited domains, worth testing in suitable experiments.

III. 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 ρ, 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

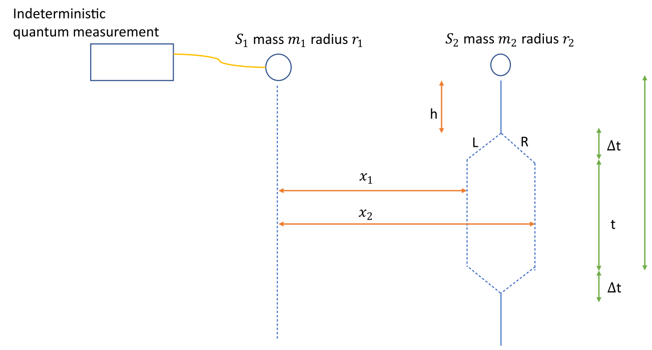

FIG. 1. Schematic description of experiment (not to scale). An indeterministic quantum measurement outcome is relayed by a small electrical pulse to an apparatus that (for example by switching a magnetic field) either holds or releases the sphere S_1 at time $t = 0$. At the same time, S_2 is released, falling under gravity through a Stern-Gerlach interferometer. Distances are represented by orange arrows, and times of fall by green arrows. Paths with amplitude 1 are represented by solid blue lines, and paths with smaller amplitudes by dotted blue lines.

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 $x_1 < x_2$. These times and separations are all defined in the laboratory rest frame. (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), is 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 the 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 difference between the two paths and its state after time t is

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

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

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

where

$$\phi_L = \frac{Gm_1m_2}{\hbar x_1}, \qquad \phi_R = \frac{Gm_1m_2}{\hbar x_2}. \tag{7}$$

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

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

If

$$(\phi_R - \phi_L)t \approx 1, \tag{9}$$

or more generally if $(\phi_R - \phi_L)t \bmod 2\pi$ is significantly nonzero, we can distinguish Eqs. (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 semiclassical 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 also needs to allow for the gravitational self-interaction predicted by semiclassical 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 semiclassical 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 [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 [38]. Our proposed experiment is also less constrained in that we are free to take $m_1 \gg m_2$, which allows Eq. (9) to hold for smaller masses m_2 than those considered in Refs. [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.* [34] suggested spheres of radius $r = 10^{-6}$ m with masses $m_1 = m_2 = 10^{-14}$ kg, and separations (in their case between the nearest path of S_1 to the paths of S_2) of $x_1 = 2 \times 10^{-4}$ m, $x_2 = 7 \times 10^{-4}$ m, with the paths adjacent for time $t = 2$ 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 $x_1 \ll x_2$

$$(\phi_L - \phi_R)t \approx \frac{Gm_1m_2t}{x_1\hbar}. \tag{10}$$

In our proposed experiment, in principle, we could retain the value of $m_1 \approx 10^{-14}$ kg and take x_1 significantly smaller, perhaps as far as $x_1 \approx 2 \times 10^{-6}$, allowing m_2t to be 2 orders of magnitude smaller. Alternatively, while keeping $x_1 \approx 2 \times 10^{-4}$ m and $x_2 \approx 7 \times 10^{-4}$ m, the sphere S_1 could be made significantly larger and more massive. Taking S_1 of radius $\approx 10^{-4}$ m gives $m_1 = \frac{4}{3}\pi\rho r_1^3 \approx 10^{-8}$ kg, which would allow $m_2 t$ to be 6 orders of magnitude smaller.

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

$$(\phi_L - \phi_R)t \approx \frac{G m_2 t x_1 \Delta x}{\hbar}, \tag{11}$$

where Δx 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 nontrivial. 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.

IV. DISCUSSION

The experiments we propose test quantum gravity against semiclassical gravity or some other quasiclassical theory on small scales, in the neighborhood of a measurement-like quantum event, where any anomalous effects seem likeliest. Compared to the beautiful experiments discussed in Refs. [34,37], which also test quantum gravity against quasiclassical gravity models, they allow more freedom in the experimental parameters and so appear likely to be possible sooner. There is a persuasive case [34,37,39] 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 semiclassical gravity would be excluded by detecting entanglement in the experiments of Refs. [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 semiclassical 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. [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. [34,37] 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 [40] to probe the collapse locality loophole [41,42]. As in Ref. [40], 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., Ref. [42] 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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