

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

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All existing quantum-gravity proposals are extremely hard to test in practice. Quantum effects in the gravitational field are exceptionally small, unlike those in the electromagnetic field. The fundamental reason is that the gravitational coupling constant is about 43 orders of magnitude smaller than the fine structure constant, which governs light-matter interactions. For example, detecting gravitons—the hypothetical quanta of the gravitational field predicted by certain quantum-gravity proposals—is deemed to be practically impossible. Here we adopt a radically different, quantum-information-theoretic approach to testing quantum gravity. We propose witnessing quantumlike features in the gravitational field, by probing it with two masses each in a superposition of two locations. First, we prove that any system (e.g., a field) mediating entanglement between two quantum systems must be quantum. This argument is general and does not rely on any specific dynamics. Then, we propose an experiment to detect the entanglement generated between two masses via gravitational interaction. By our argument, the degree of entanglement between the masses is a witness of the field quantization. This experiment does not require any quantum control over gravity. It is also closer to realization than detecting gravitons or detecting quantum gravitational vacuum fluctuations.

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Contemporary physics is in a peculiar state. The most fundamental physical theories, quantum theory and general relativity, claim to be universally applicable and have been confirmed to a high accuracy in their respective domains. Yet, it is hard to merge them into a unique corpus of laws. We still do not have an uncontroversial proposal for quantum gravity. Some approaches are based on applying a quantization procedure to the gravitational field [1], in analogy with the electromagnetic field; some others are based on “geometrizing” quantum physics [2], while others modify both into a more general theory (e.g., string theory [3]) containing both quantum physics and general relativity as special cases. All of them are affected by acute technical and conceptual difficulties [4–6].

There is, however, an even more serious problem. Current proposals for quantum gravity lead to seemingly untestable predictions [7,8]. On this ground, some have even argued that quantizing gravity is not needed after all [9] or that gravity may not even be a fundamental force [10,11]. Ronsfeld summarized the problem as follows: “the incorporation of gravitation into a general quantum theory of fields is an open problem, because the necessary empirical clues for deciding the question of the quantization of the gravitational fields are missing. It is not so much a matter here of the mathematical problem of how one should develop a quantum formalism for gravitation, but rather of the purely empirical question, whether the gravitational field—and thus also the metric—evidence quantumlike features” [12].

How would one confirm experimentally that the gravitational field has “quantumlike features”? A good starting point, though not sufficient, is a thought experiment Feynman proposed during the Chapel Hill conference on gravity [13]. A test mass is prepared in a superposition of two different locations and then interacts with the gravitational field.

Then, the gravitational field and the mass would presumably become entangled (Feynman used different terminology, but that is what a fully quantum treatment would imply). To conclude that the field must be quantized, Feynman proposed to perform a full interference of the mass. If the mass did interfere, Feynman’s reasoning goes, gravity would be quantum since reemerging the two spatial branches would then reverse the coupling to gravity, confirming the unitary dynamics in quantum theory. Of course, Feynman also acknowledged that quantum theory could stop applying at a certain scale. This would then presumably constitute a new law of nature—for instance, see the existing “gravitational collapse” literature [9,14,15].

Even if successful in showing the full interference of a single macroscopic mass, Feynman’s thought experiment is not enough to conclude that the gravitational field is quantum. This is because his proposed interference only requires that the two spatial states of the mass acquire different phases during the experiment. These phases could simply be induced by interaction with an entirely classical gravitational field, without ever requiring entanglement between the mass and the field. There is indeed a long

history of witnessing such phases induced by classical gravitational fields. Prominent examples are the Collella-Overhauser-Werner and related experiments [16], where the phase of a single-neutron interferometer is controlled by the Earth's Newtonian gravitational potential. Another more recent proposal for a proof-of-principle experiment, involving general relativistic effects on quantum systems [17,18], relies on the gravitational redshift caused by the Earth's gravitational field affecting the phase of an interference experiment with atomic clocks. All such experiments (see also [19]) are compatible with the gravitational field being completely classical; this is indeed the main assumption under which their predicted outcomes are derived.

So, a gravitationally induced phase on the quantum state of a single mass does not constitute experimental evidence of the quantization of gravity. Instead, one would have to show that the gravitational field is capable of existing in a superposition of different values. The key here is to be able to witness the presence of another observable in the field that does not commute with the first one. This is precisely what one means by the field being quantum: it must have at least two noncommuting observables.

We show here that it is possible to witness quantum features of the field by probing it with *two* masses. Intuitively, the first mass, being in a superposition of two locations, becomes entangled with the field, while the second mass, also in a superposition, is used to witness that entanglement [20]. This is a fundamentally different approach to detecting quantum effects in the gravitational field, based on a quantum-information-theoretic method that requires no quantum manipulation of the gravitational field itself. First, we prove the fact that if two quantum systems (e.g., two masses that can be spatially superposed) become entangled through an interaction with a third system (e.g., the gravitational field), then that third system must itself be quantum—in the above sense of having two noncommuting observables. This argument is general in that it could apply to any system be it continuous (like a field) or discrete (like a spin). It is also independent of the exact details of the dynamics, along the lines of [21,22]. Interestingly, this makes our proposal independent of particular models of quantum gravity. This is an advantage given that there are many different proposals.

Then, we propose an experiment, based on our theoretical argument, in which the two quantum systems are two masses each spatially superposed. The third mediating system is the gravitational field. Via our theoretical argument, the entanglement between the positional degrees of freedom of the masses is an indirect witness of the quantization of the gravitational field. As we see, the entanglement between the masses is a function of the relative phase acquired by each of the masses along the paths, via their interaction with the gravitational potential generated by the other superposed mass. This experiment,

as we illustrate, is feasible with current technology, using some form of matter-wave interferometry—e.g., [23–25]. Our experiment only relies on having the full quantum control over the two masses.

Consider now three physical systems: two quantum systems Q_1 and Q_2 (e.g., the two quantum masses in our experiment) and a third system C (e.g., the field mediating the interaction). Suppose that C is “classical,” by which we mean that C has only a single observable T . This notion of classicality is information theoretic [21,22] and sharply differs from other existing ones—e.g., the field being in a coherent state, or its being a decoherent channel [26].

For simplicity, we assume that Q_1 and Q_2 are qubits. Let $\hat{q}^{(1)} \doteq (\sigma_x \otimes I_{2,c}, \sigma_y \otimes I_{2,c}, \sigma_z \otimes I_{2,c})$ denote the vector of generators $q_\alpha^{(1)}$ of the algebra of observables of the qubit Q_1 , where σ_α , $\alpha = x, y, z$ are the Pauli operators and $I_{2,c}$ is the unit on Q_2 and C . Let $\hat{q}^{(2)}$ be defined in a similar way. We also assume that the classical system C is a bit, i.e., T is a binary observable. Without loss of generality, we can represent it as an operator $q_z^{(C)} \doteq I_{12} \otimes \sigma_z$, where I_{12} is the unit on $Q_1 \oplus Q_2$. In our proposed experiment, T might be a discretized version of one of the quadratures of the gravitational field. The argument, however, would apply to continuous systems too (e.g., a harmonic oscillator).

Now, consider an experiment where Q_1 , Q_2 , and C are initially disentangled. For example, they are each one independently prepared in an eigenstate of σ_z . Suppose Q_1 interacts with C and Q_2 interacts with C , separately; but Q_1 and Q_2 never interact directly. Suppose that after these interactions Q_1 and Q_2 are confirmed to be entangled. Entanglement is confirmed by directly measuring observables on Q_1 and Q_2 only, in a different basis, to implement a witness—but no measurements are ever performed on C (despite the fact that it could be measured in its own classical basis).

That Q_1 and Q_2 are entangled is in contradiction with C being classical, thus proving that it must have at least another complementary observable in addition to T . This is because, if C is classical, the most general form of a state of $Q_i \oplus C$ is

$$\rho = \frac{1}{4} (I_{12,c} + \underline{r} \cdot \hat{q}^{(i)} + s_z q_z^{(C)} + \underline{t} \cdot \hat{q}^{(i)} q_z^{(C)}),$$

for some real-valued vectors \underline{r} , \underline{t} and for some real coefficient s_z ($I_{12,c}$ is the unit on $Q_1 \oplus Q_2 \oplus C$). This state, when interpreted as a two-qubit state, is separable. Hence, the most general state of the system $Q_1 \oplus Q_2 \oplus C$, if the three systems start globally disentangled and Q_1 and Q_2 can never directly interact, will also be separable. In particular, the state of $Q_1 \oplus Q_2$ will be separable. Hence, if Q_1 and Q_2 are found in an entangled state and if that entanglement has been mediated by the interaction

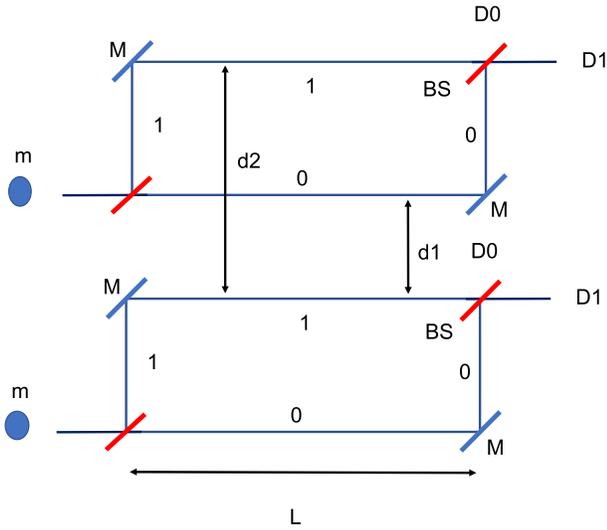


FIG. 1. Entanglement-based witness of quantum gravity with two equal masses. Each mass m individually undergoes Mach-Zehnder-type interference, and interacts with the other mass via gravity. BS indicates a beam splitter; M indicates a mirror; D_i with $i = 0, 1$ indicates the detector on path i . L is the length of the lower arms of each interferometer. The distance between the lower arms of the two interferometers is d_1 and the distance between the upper arm of one interferometer and the lower arm of the other interferometer is d_2 . See the full description in the text.

with C , C must have itself at least another observable complementary to T .

Now, a field can be considered as a collection of systems C_i each one being a harmonic oscillator, mediating the interaction between two quantum systems Q_1 and Q_2 that can couple to the field. The collection of systems C_i can itself be regarded as a classical system C . Any interaction between Q_1 and Q_2 mediated by the field can be modeled as an interaction between Q_1 and C , and then between C and Q_2 . By applying the same argument as above, if Q_1 and Q_2 can be entangled via the field, the field must be quantum in the above sense. Unlike other witnesses of nonclassicality (e.g., [27]), our argument does not assume any specific dynamics. The only assumption here is that the interactions must be local—namely, there cannot be any action at a distance between Q_1 and Q_2 , and that Q_1 interacts with C only, and so does Q_2 .

It is of course always possible to generate entanglement between Q_1 and Q_2 by using a classical system C as the control of a controlled unitary on $Q_1 \oplus Q_2$. For example, the unitary could act so that if C is in a certain state of its classical basis, a unitary prepares the system $Q_1 \oplus Q_2$ in a particular entangled state. However, generating that entangled state would require Q_1 and Q_2 to interact directly with one another, which violates our locality assumption. Note that we have, for present purposes, ignored the possibility of using nonlocal features of the geometry of spacetime, such as closed timelike curves [28]. It is not excluded that by allowing such features one might be able

to establish entanglement nonetheless via local interactions with C . Note also that it would not be possible to apply, in this context, well-known results of quantum information theory, such as the fact that Local Operations and Classical Communication cannot increase the entanglement between two spatially separated parties [29]. This is because those results assume that all the systems involved obey quantum theory. Here, instead, the gravitational field cannot be assumed to obey quantum theory (the experiment is precisely designed to assess whether it does). This is why one must resort to the more general argument we propose.

We turn now to our experimental proposal—see Fig. 1. Two quantum systems Q_1 and Q_2 with equal mass m are entangled only via the gravitational field—which plays the role of the system C . Our argument implies that the entanglement between $Q_1 \oplus Q_2$ is an indirect witness of nonclassicality of gravity—i.e., of the noncommutativity of the observables on the gravitational field. Specifically, each mass is in one of two Mach-Zehnder interferometers, each located so that both masses are subject to the same Earth’s gravitational field (for example, parallel to the Earth’s surface). The lower interferometer arm is indicated by 0 and the upper arm by 1. Each mass is put in the state $1/\sqrt{2}(|0\rangle + |1\rangle)$ by the first beam splitter.

Since the masses on different paths interact via the gravitational field, the state of the composite system becomes, before they enter their respective final beam splitters,

$$\frac{1}{2} |0\rangle[|0\rangle + \exp(i\phi_1)|1\rangle] + \frac{1}{2} \exp(i\phi_1)|1\rangle[|0\rangle + \exp(i\Delta\phi)|1\rangle], \quad (1)$$

where ϕ_1 and ϕ_2 are the relative phases acquired by the masses due to the gravitational potential generated when they are, respectively, at distance d_1 and d_2 from one another; $\Delta\phi = \phi_2 - \phi_1$ is their difference. We suppose that the gravitational interaction of the masses on the two most distant arms is negligible. Supposing that the dominant contribution to the gravitational interaction is Newtonian, and that the general-relativistic contributions are negligible, the value of the phase is $\phi_i = (m^2 G / \hbar d_i) \Delta t$, where G is the gravitational coupling constant, $\Delta t = L/v$ is the time spent by each mass on the horizontal arm of the interferometer, of length L , and v is their velocity. However, the conclusion as for the quantization of the gravitational field would be the same no matter what type of field mediates the entanglement. It is remarkable, though, that even the Newtonian contribution already demonstrates the quantum nature of gravity.

Depending on the particles’ mass, the distance between the two interferometers, and the length of the arms, the above state is entangled to a different degree. The mutual

interaction of each of the masses acts as a measurement of which path they are on: depending on the phases, that interaction may completely destroy the interference effect of each mass, showing maximal entanglement.

In each of the interferometers, the probabilities p_α for the mass to emerge on path $\alpha = 0, 1$ are

$$\begin{aligned} p_0 &= \frac{1}{2} \left(\cos^2 \frac{\phi_1}{2} + \cos^2 \frac{\Delta\phi}{2} \right), \\ p_1 &= \frac{1}{2} \left(\sin^2 \frac{\phi_1}{2} + \sin^2 \frac{\Delta\phi}{2} \right). \end{aligned} \quad (2)$$

There are two extreme regimes. One is when the two masses are maximally entangled by the action of the gravitational field, in which case $p_0 = p_1 = \frac{1}{2}$. This happens when $\phi_1 = 2n\pi$, $\Delta\phi = \pi$ for some integer n . The other extreme is when the two masses are not entangled and undergo, separately, an ordinary interference experiment: that happens when $\phi_1 = \Delta\phi = 2n\pi$. In this case, each mass emerges on path 0 of the interferometer. For a fixed mass, by varying the arms' distance or their length, it is, in principle, possible to interpolate between those two cases, thus demonstrating all degrees of entanglement, ranging from no entanglement to maximum. By our argument, this entanglement is a witness that the gravitational field that mediated the interaction must be quantum.

Feasibility considerations suggest that the experiment can be realized with existing technologies. The two masses could be massive molecules, as in [23], two split Bose condensates [25], or two nanomechanical oscillators [24]. For example, two coupled nanomechanical oscillators of mass 10^{-12} kg interacting for a $\Delta t = 10^{-6}$ s would achieve the extreme phase shifts, over distances $d \approx 10^{-6}$ m. The main difficulty with the experiment is that any other effects on the masses must be made smaller than the gravitational interaction. But there are other important subtleties that we proceed to discuss.

Failing to detect entanglement would not imply that gravity is not quantum. It could be that our model is inadequate, because the interaction between the field and the masses contains higher order correlations. In our analysis we have added up the phases linearly (as one would do for the electromagnetic case), but this need not apply to gravity [30]. It could also be that the field is quantum, as defined above, but it is a decoherent channel—as discussed in [26]. In this case, the field would have noncommuting degrees of freedom, but they would be so decohering that the channel could never transmit any entanglement (i.e., it would be “entanglement breaking”). The type of decoherence depends on the particular implementation for our proposed experiment. For example, for nanomechanical oscillators, the time scale for decoherence can be expected to be in the range of μ s to ms [31,32]; therefore any time interval below μ s would be acceptable.

If the experiment succeeded in detecting entanglement between the masses, one would have to make sure that it is really generated mainly by gravity. There could be other sources of interaction between the masses that would lead to entanglement—for example, the Van der Waals forces or other electromagnetic interactions. If they were much stronger than gravity, we could not conclude anything about the quantization of gravity. However, if they were comparable, it might still be possible to isolate the characteristic $1/r$ behavior of the gravitational potential in the phase (as opposed for example to the Lennard-Jones $1/r^6$), in which case the proposed scheme might still apply. Finally, detecting entanglement, even when it is generated only through gravity, does not indicate which model of quantized gravity one must adopt. Whatever the model, the conclusion is that the field must have at least two non-commuting observables. What these observables are remains an open question (see Supplemental Material [33] for further speculations).

It is illuminating to analyze how the two field observables entangle the two masses, if the field indeed is quantum. First, each mass becomes entangled with the field, interacting with one of the field's observables. This is exactly what Feynman had in mind for a single mass. Then the phases are induced into each of the four massive configurations (as in Fig. 1) via the interaction between the masses and the other observable of the field. Finally, the field becomes disentangled from the masses as they emerge from the interferometer (again as would happen in Feynman's experiment with a single mass).

Remarkably, our proposal works even if the entanglement between the masses and the field is very small, because it relies on detecting only the entanglement between the positions of the two masses. In fact, the entanglement between the field and the masses may never even be detectable in practice just like a spontaneous emission of a graviton [7]. Still, it is sufficient to generate the phases leading to entanglement between the masses.

Since our proposal does not rely on any specific dynamics, it could also be applied to prove the quantization in different scenarios. For example, one could think of variants of the Aharonov-Bohm (AB) effect, where the solenoid interacting with a quantum charge is replaced by a small current caused by another quantum charge, generalizing recent proposals to explain the AB effect purely in terms of quantum entanglement [35].

The key next steps are to identify the best physical implementation of our proposal, provide a detailed analysis of all the relevant effects that could compete with gravity, and perform a comparative study of how this experiment would be modeled in different approaches to quantum gravity.

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Note added.—Recently, we became aware of a related parallel independent work [36].

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