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]

[1]*Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, England, United Kingdom*
[2]*Blackett Laboratory, Imperial College, London SW7 2BZ, England, United Kingdom*
[3]*Center for Astroparticle Physics and Space Science (CAPSS), Bose Institute, Kolkata 700 091, India*
[4]*Van Swinderen Institute, University of Groningen, 9747 AG Groningen, The Netherlands*
[5]*School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, England, United Kingdom*

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A defining signature of classical systems is "in principle measurability" without disturbance: a feature manifestly violated by quantum systems. We describe a multi-interferometer experimental setup that can, in principle, reveal the nonclassicality of a spatial superposition-sourced gravitational field if an irreducible disturbance is caused by a measurement of gravity. While one interferometer sources the field, the others are used to measure the gravitational field created by the superposition. This requires neither any specific form of nonclassical gravity, nor the generation of entanglement between any relevant degrees of freedom at any stage, thus distinguishing it from the experiments proposed so far. This test, when added to the recent entanglement-witness based proposals, enlarges the domain of quantum postulates being tested for gravity. Moreover, the proposed test yields a signature of quantum measurement induced disturbance for any finite rate of decoherence, and is device independent.

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Introduction—As far as empirical evidence is concerned, nature is described accurately as a hybrid of quantum field theories (all matter and three of the forces) and a classical theory of gravity (general relativity). However, matter sources gravity, and thereby an unresolved age old question is whether the gravitational field of a mass in a spatial quantum superposition is quantum or classical [1–6]. "Ruling out" gravity as a classical field or curvature by creating large enough masses in such quantum superpositions, although challenging [6–14], is potentially less demanding than detecting quantum corrections to gravitational interactions [15] or on-shell gravitons [16–19]. In this respect, a major progress has been made recently, with the proposal to entangle two masses in quantum superpositions through their gravitational interaction [20–22]. Although the gravitational interaction between the masses is, to any degree of near-term testability, purely Newtonian, it can be argued that the generation of this entanglement between the masses necessitates a quantum superposition of geometries [23]. Several persuasive arguments have been put forward linking this experiment with the nonclassicality of gravity [24–30] and several variants have been proposed [31–36].

The principal obstacle of the above proposal [20–22] is decoherence. If the decoherence rate $\Gamma > d\Delta\phi/dt$, where $d\Delta\phi/dt$ is the rate of growth of the phase responsible for gravity induced entanglement, then no entanglement is produced between the masses [37–39] (verifiable using the Peres-Horodecki criterion [40,41]). Moreover, witnessing entanglement requires trusted measurement devices. Although one may use device-independent detection of entanglement through the Bell test [36], that demands an even lower decoherence rate [42], as well as closing all loopholes, which is challenging. Thus the key question is whether some *other* nonclassical aspect of gravity can be observed in the $\Gamma > d\Delta\phi/dt$ regime, which will be detectable much *earlier* in experiments. Notably, a coherence $\sim e^{-\Gamma t}$ is always present in any spatial superposition of a mass evolved for a time t. Can that be exploited to observe some nonclassicality of gravity? Motivated thus, here we propose to test a different nonclassical aspect of gravity, which is, at the same time, a device-independent test, and works for any finite decoherence rate. While entanglement witnessing [21,22] tests the validity of quantum superposition principle for gravity, our present proposal can test *whether* a measurement of gravity generically causes disturbance (an irreducible feature of quantum measurement).

[*]Contact author: farhan.hanif.17@ucl.ac.uk
[†]Contact author: debarshi.das@ucl.ac.uk
[‡]These authors contributed equally to this work.

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As quantum mechanics is not defined by the superposition principle alone, but also requires the unitarity of evolution and the measurement postulate [45,46], witnessing entanglement in the earlier proposal [21,22] will imply that gravity is described either by quantum mechanics, or by a (unknown) nonclassical theory that obeys superposition principle. To know whether gravity is indeed quantum, we need to test other quantum mechanical postulates for gravity. This is a gap in the literature that we hereby fill by proposing to test a specific aspect of the quantum measurement postulate, namely, quantum measurement-induced disturbance. Adding this test to the entanglement-witness based test [21,22] will take us towards a more *complete* demonstration of gravity as a quantum entity.

An ideal measurement on a classical field should not, *in principle*, alter the state of any system (other than, obviously, the state of the probe which registers the field) [47]. In fact, that should be taken as a crucial part of the definition of any classical field, followed from our everyday notion of classicality [48]. This leads to the testable "nondisturbance condition" (NDC) [49–51]: The act of performing an intermediate measurement should not influence the outcome statistics of a subsequent measurement. Observing a discrepancy between intermediately measured and intermediately unmeasured statistics would thus be a signature of nonclassicality. In practice, a clumsy measurement on a classical field can cause disturbance (classical disturbance). Crucially, this disturbance is not an inherent part of classical physics—one can arbitrarily reduce it by performing the measurement appropriately. On the other hand, the quantum measurement-induced disturbance is an intrinsic part of quantum theory, which *cannot* be eliminated by any means. This feature is central to our proposal to show the irreducible nonclassicality of gravity.

Schematics—We first present the general idea as a schematic. A source mass described by quantum mechanics, but large enough to produce a detectable gravitational field at a proximal detector, is made to undergo an interferometry with equal amplitudes in the arms (labeled by quantum states $|L\rangle$ and $|R\rangle$). The outputs at the end of the interferometry (which could be direct electromagnetic detection of the source mass) are labeled $+$ and $-$, while the relative phase $\Delta\lambda$ between the arms is ensured to be 0. This setting [Fig. 1(a)] is then compared with another setting [Fig. 1(b)], where an intermediate gravitational field detector is placed during the interferometry. In practice, the most sensitive such detector will be similar mass (masses) undergoing interferometry (interferometries). *It is crucial to ensure that the detector performs an intermediate measurement (midway during the interferometry) of the gravitational field of the source mass rather than the position of the source mass itself by other means (i.e., via electromagnetic channels, or scattered photons).* Without considering any specificity of the information obtained

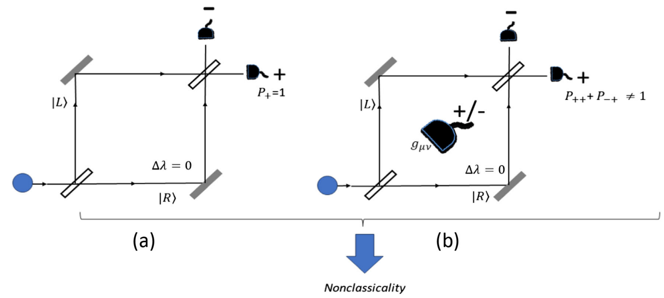

FIG. 1. A source mass is prepared in a superposition of states $|L\rangle$ and $|R\rangle$ by subjecting it through an ideal Mach-Zehnder interferometer, while ensuring no interferometric phase difference between the arms ($\Delta\lambda = 0$). (a) Given that no intermediate measurement is performed, the final detector outcome is certain to be $+$: $P_+ = 1$. (b) An intermediate measurement of the gravitational field of the source mass is performed by a suitable detector (Schematically shown as the large detector measuring the metric $g_{\mu\nu}$). This measurement has two outcomes ($\pm$). If, after this intermediate detection, the final outcome probability (averaged over outcomes of the intermediate measurement) differs from unity, it implies that gravity is nonclassical.

through the measurement, we assume that this measurement gives one bit of information about the gravitational field with outcomes depicted by $+$ and $-$. Subsequently, a detection of the source mass is also made in the $+$ and $-$ outputs of the interferometer. If a "hybrid model" is used with quantum matter, but classical gravity, then, by definition (of classicality), the measurement of gravity by the intermediate detector cannot cause any change in the final probabilities, i.e.,

$$P_+(\text{no intermediate meas}) - P_+(\text{after intermediate meas}) = 0, \quad (1)$$

where $P_+(\text{after intermediate meas}) = P_{+,+} + P_{-,+}$ (here $P_{a,b}$ is the joint probability of getting the outcomes a, b in the intermediate and the final measurements respectively). Equation (1) is the NDC to be satisfied by gravity as a classical entity. Any violation of this NDC implies that gravity is nonclassical. Here, we must ensure that $\Delta\lambda = 0$ is still maintained while going from the case of Fig. 1(a) to Fig. 1(b) even though an extra intermediate detector is coupled, as otherwise the probability of P_+ can simply change due to an interferometric phase difference rather than due to the measurement.

Any NDC violation in our experiment will rule out hybrid models (classical gravitational field sourced by quantum matter) for which the gravitational field can, by definition, be measured without disturbance. Examples of hybrid models [2,4,52–55] satisfying NDC can be found in [42]. Here we emphasize the necessity of both parts of the experiment. Figure 1(a) alone reveals nothing about the *form* of gravity sourced by the source mass as no gravitational field is measured at any stage. On the other hand,

Fig. 1(b) alone does not tell whether the source mass superposition has already been affected even before the measurement (e.g., as in a spontaneous collapse model [2]). Thus any proposal involving Fig. 1(b) alone, *without* comparing to Fig. 1(a) (e.g., [56]) is insufficient on its own to reveal nonclassicality of gravity.

Interferometric setup—We consider a specific arrangement in which the source mass M with an embedded spin undergoes a spin dependent spatial interferometry (also called a Stern-Gerlach interferometry [12]). This replaces the Mach-Zehnder interferometer depicted in Fig. 1. The unmeasured case [corresponding to Fig. 1(a)] of the experiment is performed only with this mass. The intermediate detector for measuring the gravitational field of the source mass [corresponding to Fig. 1(b)] is realized by two successive probe interferometers, each with mass m and an embedded spin, arranged in a geometrically parallel configuration with respect to the source interferometer at some distance d away. The spatial superposition of the source mass is then closed and a projective measurement is performed on its embedded spin. The protocol is depicted in Fig. 2. We finally compare the statistics of the final spin measurement with and without the intermediate gravitational field measurements to test the NDC.

All masses are prepared, held in spatial superposition (mechanism to create such superposition can be found in [6–14]), and recombined for completing interferometry through specific means, such as spin motion coupling. In what follows, let M_i and S_i denote the mass and embedded spin degrees of freedom of a given mass indexed by i according to whether one of the two probe systems ($i = A$, B in sequence) or the source system ($i = C$) is referenced.

The initial state of the source mass with its embedded spin at $t = 0$ is given by

$$|\psi(t=0)\rangle = |\zeta\rangle_{M_C} \otimes \frac{1}{\sqrt{2}}(|\uparrow\rangle_{S_C} + |\downarrow\rangle_{S_C}),$$

where $|\zeta\rangle_{M_C}$ is the initial localized state of the source mass at the center of the axis of the source interferometer. Over a time T, the source mass is prepared in spatial superposition via the unitary evolution:

$$|\zeta\rangle_{M_C} \otimes |\uparrow\rangle_{S_C} \to |L\uparrow\rangle_C, \quad |\zeta\rangle_{M_C} \otimes |\downarrow\rangle_{S_C} \to |R\downarrow\rangle_C. \tag{2}$$

In the above, the states $|L\uparrow\rangle_C$ and $|R\downarrow\rangle_C$ are separated by a distance $\Delta x(t)$, which grows from 0 at $t = 0$ to the maximum at $t = T$ with $\Delta x(T) = \Delta x$. The first probe mass M_A (of mass m) with embedded spin S_A is then introduced and subjected to the evolution (2) with the subscript "C" being replaced by "A" over another time interval T.

With both superpositions fully prepared, the source and the probe now interact exclusively through gravity in a static geometrical arrangement for a time τ before the spatial superposition of the probe is closed over a time

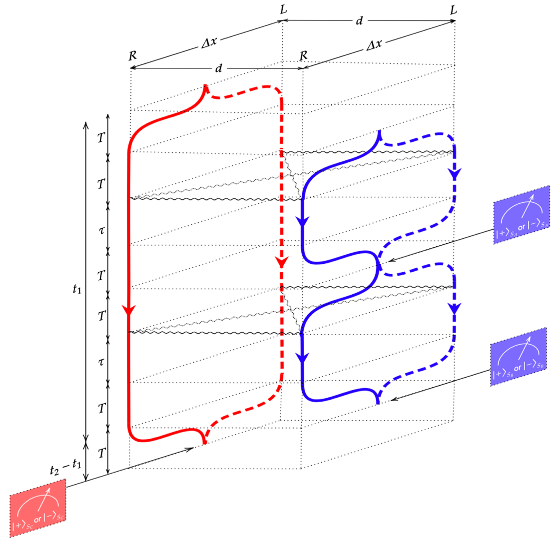

FIG. 2. The gravitational field generated by the interferometric source mass (red) is measured sequentially by a pair of massive interferometric probes (blue), where the gravitational interactions are indicated by wavy lines. Finally, the source mass superposition is closed and a measurement is performed on the embedded spin of the source mass.

T [12,21]. Thus the total interaction time interval is $2T + \tau$. At this stage, the joint state of the source and probe is given by

$$|\psi\rangle_{C,A} = \frac{1}{\sqrt{2}}\Big(\sqrt{1+\cos\Delta\phi}|\Psi_+\rangle_C|+\rangle_{S_A} + \sqrt{1-\cos\Delta\phi}|\Psi_-\rangle_C|-\rangle_{S_A}\Big)|\zeta\rangle_{M_A}, \tag{3}$$

with

$$|\Psi_\pm\rangle_C = \frac{(1 \pm e^{i\Delta\phi})|L\uparrow\rangle_C + (e^{i\Delta\phi} \pm 1)|R\downarrow\rangle_C}{2\sqrt{1\pm\cos\Delta\phi}}$$
$$|\pm\rangle_{S_A} = \frac{|\uparrow\rangle_{S_A} \pm |\downarrow\rangle_{S_A}}{\sqrt{2}}, \tag{4}$$

where $\Delta\phi = \Delta\phi_\tau + 2\Delta\phi_T$ is a function of the relative phases accumulated between the different arms of the source and each of the probe interferometers over their total interaction time duration $2T + \tau$. Of its constituent parts, $\Delta\phi_T$ is the relative phase accumulated during the opening or the closing of the spatial superposition of each probe, with its expression being somewhat elaborate (given in [42]), while $\Delta\phi_\tau$ is associated with the relative phase development for the duration τ when the spatial superpositions of source and each probe are held in a static geometrical arrangement and is given by

$$\Delta\phi_\tau = \frac{GMm\tau}{\hbar\sqrt{d^2 + (\Delta x)^2}} - \frac{GMm\tau}{\hbar d}. \tag{5}$$

Note that the probe mass is not affected by contact (or otherwise electromagnetically) with the source mass, but only being affected at a distance by the source's gravity (i.e., through the metric g_{00}, which is completely determined by the source mass). After closure of the interferometry of the probe, its spin state is decoupled from its spatial state which enables accessing the information about the relative phases accumulated between $|L\uparrow\rangle_A$ and $|R\downarrow\rangle_A$ due to gravitational interaction between the source and the probe. Accordingly, a projective measurement of the probe spin is now performed in the $|\pm\rangle_{S_A}$ basis. This projection results in a POVM on the source system (mass and its associated field). Since only the gravitational field of the source is in contact with the probe, we can say that this POVM is essentially a measurement of gravity.

The first probe is then discarded, and a new probe is introduced. As before, the new probe now interacts with the source system via the gravitational field for a further time $2T+\tau$ in an identical fashion before a projective measurement in the $|\pm\rangle_{S_B} = (|\uparrow\rangle_{S_B} \pm |\downarrow\rangle_{S_B})/\sqrt{2}$ basis is performed on the spin degree of freedom of the second probe at $t = t_1 = 5T + 2\tau$. As argued earlier, this is also a measurement of the source's gravity. The second probe is then also discarded. Over a time T, the spatial superposition of the source interferometer is now closed via the reversal of the unitary evolution (2).

A final projective measurement of the source spin is then performed in the $|\pm\rangle_{S_C} = (|\uparrow\rangle_{S_C} \pm |\downarrow\rangle_{S_C})/\sqrt{2}$ basis at $t = t_2$ where $t_2 - t_1 = T$. This measurement yields the following unnormalized states of the source conditioned on the outcomes of the three measurements (for details, see [42]):

$$|\psi_{a,b,c}\rangle = \frac{1}{8}\big[(1+ae^{i\Delta\phi})(1+be^{i\Delta\phi}) + ce^{2i\Delta\phi}(1+ae^{-i\Delta\phi})(1+be^{-i\Delta\phi})\big]|\zeta\rangle_{M_C}|c\rangle_{S_C},$$

where $a, b, c \in \{+,-\}$ denote the outcomes of the first and second probe measurements followed by the final measurement on the source spin respectively. From the norms of these states, the joint probabilities $P_{a,b,c}$ are obtained.

Let us now consider the same scenario as described above, except that the probes are not introduced, and thus no intermediate measurement takes place prior to the final measurement on the source spin at $t = t_2$. In this case, the probabilities of the final measurement outcomes are $P_+ = 1,\ P_- = 0$.

Thus the violation of the NDC is given by [42],

$$V(\pm) = P_\pm - \sum_{a,b\in\{\pm\}} P_{a,b,\pm} = \pm\frac{1}{2}\sin^2\Delta\phi. \tag{6}$$

This NDC violation implies that measurement of gravity causes disturbance. Notably, NDC violation persists (although suppressed) for any finite rate of decoherence [42].

This is a device-independent test of nonclassicality in the sense that the intermediate and the final measurements need not to be trusted. We only need to ensure that the intermediate measurements are on the source's gravitational field.

While the calculations [42] are carried out under the application of an instantaneous, manifestly nonlocal Newtonian field, this is merely a *calculational tool* that yields outcomes consistent with a relativistic description [24,25,30].

Is entanglement between the source and the probe necessary?—Equation (3) implies that entanglement is created between the source and the first probe (similarly for the second probe). This is obtained following the usual quantum formalism and is the core of the earlier proposal [21,22]. Now, let us consider another hypothetical nonclassical theory of gravity (different from quantum theory), where the gravitational interaction between the source and the probe produces the following separable joint state (following some unknown mechanism),

$$\rho_{C,A} = \frac{1}{2}\big((1+\cos\Delta\phi)|\Psi_+\rangle_C\langle\Psi_+|_C \otimes |+\rangle_{S_A}\langle+|_{S_A} + (1-\cos\Delta\phi)|\Psi_-\rangle_C\langle\Psi_-|_C \otimes |-\rangle_{S_A}\langle-|_{S_A}\big) \otimes |\zeta\rangle_{M_A}\langle\zeta|_{M_A}.$$

In this case, classical correlation created between the source and the probe is sufficient to perform measurement of the source's gravity. Following similar gravitational interaction between the source and the second probe, the same NDC violation (6) is obtained. If gravity obeys such a nonclassical theory, then the previous proposal [21,22] fails as no gravity-induced entanglement is generated. However, the present proposal can witness nonclassicality of gravity in such a case. This establishes the independence of the present proposal with respect to the previous one [21,22].

Why two probes—Quantum measurements, accompanied by an averaging over the outcomes, essentially cause a *dephasing* of the source mass. This is mathematically equivalent to a probabilistic phase flip, with the probability of phase flip growing from 0 initially to $1/2$ at infinite time (complete dephasing). This is indeed at the core of violating NDC. However, we should prevent any additional deterministic phase (equivalent to $\Delta\lambda \neq 0$) caused by the presence of the probe as it can be interpreted as a classical disturbance due to a common gravitational acceleration experienced by both $|L\rangle_{M_C}$ and $|R\rangle_{M_C}$ of the source mass [57]. In our proposal, two separate probe measurements are employed to eliminate this classical disturbance [42].

Parameter regimes—To exemplify, let us consider the parameter regime with $M, m \sim 10^{-14}$ kg, and closest approach of the masses $d \sim 157$ μm to ensure that gravity is significantly stronger than the electromagnetic interactions between neutral masses [38] such that the intermediate measurements are indeed on the gravitational field. As the superposed trajectories in each interferometer are fixed through magnetic gradients [8–14], which is much stronger than the gravitational force between the masses, we can safely assume that the gravitational pull on the source due to the probe (a classical disturbance) is negligible. In practice, we must further ensure the following [49]: acting as a control experiment, a classical mixture of the two localized states $|L\rangle_{M_C}$ and $|R\rangle_{M_C}$ of the source mass should be prepared instead of a superposition, which is expected to give rise to a classical-like gravitational field. Then the detected NDC violation (which arises solely due to classical disturbance and would give zero in the ideal case) should be ensured to be at least 1 order of magnitude less than the detected NDC violation obtained by preparing the spatial superposition of the source mass under the same experimental conditions. For negligible decoherence, NDC violation $\gtrsim 0.4$ can be obtained with $\tau, T \sim 1.9$–3.2 s, and $\Delta x \sim 215$–479 μm (see [42] for details, including effects of decoherence). One can reduce M, m, d, and/or Δx by a few orders of magnitude [58] keeping the same violations. It may be easier for experiments to reduce M, m, and Δx at the price of increasing the number of runs. As NDC violation effectively amounts to measuring probabilities, we can measure a lower violation of 0.01 by averaging the results of $> 10^4$ experimental runs. The requirements on pressures, temperatures, and inertial noises to keep the decoherence negligible in the context of the earlier proposal [21,38,59] are not strictly necessary for the present proposal, as NDC violation persists for any finite decoherence rate. For example, for the typical parameter choice of the earlier proposal [21,22], generation of entanglement requires $\Gamma t < 10^{-2}$ (with t being the total interaction time) [38,58], which is equivalent to keeping the vacuum pressure $P < 5 \times 10^{-16}$ Pa. On the other hand, in our proposal $\Gamma t \sim 1$ (equivalently, $P \sim 5 \times 10^{-14}$ Pa) can give substantial violation of the NDC.

One drawback of the present proposal (and also of the previous proposal [20–22]) is that the mass of the experimental apparatus (e.g., the magnets in the Stern-Gerlach interferometers, etc.) is ignored. However, the mass of the apparatus can cause backaction on the interference of the masses due to the equivalence principle [60,61], which may have an adverse effect on our proposal. Hence, considering this effect [61] in the context of the present proposal merits further investigation.

Conclusions—There is an existing proposal for testing the validity of the quantum superposition principle for gravity via witnessing gravity-induced entanglement [21,22]. Here, we have suggested a scheme which will *complement* that test by showing that when gravity is measured, there is an irreducible disturbance (a nonclassical feature). As we are summing over the measurement-outcomes for testing NDC, the measurement is equivalent to decoherence, but a decoherence which is controllably triggered only by the act of measurement [62]. We should point out that our present work is different from [63] where the violation of Leggett-Garg inequalities (a class of inequalities violated by nonclassical theories) is used to infer gravity-induced entanglement. The quantum disturbance due to measurement of gravity is not sought to be tested there.

The earlier proposal [21,22] tests only the final entanglement between the spins of the two masses and does not fully specify the dynamics needed to reach the state. Hence, this earlier proposal cannot verify that the probe can measure the gravitational field of the source causing an irreducible disturbance. This new physical insight will be obtained by realizing the present proposal. If the decoherence rate is too high such that no entanglement is generated between the two masses, then the earlier proposal [21,22] fails in the sense that gravity cannot be concluded as a nonclassical communication channel acting between the two masses. In such extreme cases also, the correlation (weaker than entanglement) generated between the source and the probe enables us to perform a measurement of gravity, which inevitably causes disturbance leading to observable violation of NDC. Further, our test enables us to capture nonclassicality of gravity in a landscape of theories which are neither classical (violating NDC), nor fully quantum (fundamentally unable to generate entanglement between two masses). Thus the other test [21,22] should complement the present one to proceed towards capturing the full quantumness of gravity.

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