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Abstract: A quantum theory of gravity is among the most pursued goals in physics. I present a definitive and direct experimental proof that refutes the widely believed hypothesis of quantum gravity. The detections of astrophysical gravitational waves (GW) are inferred from the differential oscillations of suspended mirrors of optical interferometers like the aLIGO detectors. If gravity is indeed quantized, then the average energy $\bar{E}$ in the minute oscillations of the mirrors, at a frequency ν, corresponds to the absorption of an integer number N gravitational quanta with total energy $E_{gw} = Nh\nu$. The coherent and coincident detections across large separations of detectors, and also the constraint of the equivalence principle, dictate that the average number of quanta $\bar{N}$ forcing the oscillations obeys $\bar{N} \gg 1$, or $1/\sqrt{\bar{N}} \ll 1$. However, the average energy $\bar{E}$ in the differential oscillations is smaller than the energy of a single quantum of GW radiation at the detected astrophysical GW frequencies. This startling finding implies that $\bar{N} < 1$, which is physically impossible if gravity is quantized. This singular contradiction refutes the long-held hypothesis that gravity is quantized.

Keywords: quantum gravity; radiation quanta; gravitational waves; intrferometric detectors; sub-quantum energy

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1. Introduction

A consistent theory that describes the quantum field mechanics of the gravitational interaction, called a 'theory of quantum gravity', is an unrealised quest in fundamental physics [1–5]. There are several reasons why the coveted goal remains inaccessible. The primary theoretical hurdle is the mutually incompatible characteristics of the theory of gravity, the General Theory of Relativity, and the theory of quantum mechanics. Unlike other interactions that are formulated as gauge theories of particle interacting through other particles that represent physical fields in space and time, gravity is described as the alteration of the very nature of space and time by massive bodies. Then it is not even obvious what the physical entities pertaining to gravity are to obey the rules of quantum mechanics. In other words, it is not clear which canonically conjugate pairs of physical variables–analogous to position and momentum in particle dynamics, or electric and magnetic potentials in electrodynamics– appear as quantum operators in an expression of a quantum commutator for gravity. In an article published more than 70 years ago, B. S. DeWitt mentioned that "gravity is nearly quantized" [6]. Many formal advances have been made, along multiple conceptual paths [1,2,7,8]. But, any progress to the final goal remains both a technical challenge and a conceptual enigma. The other important and crucial reason for not realising the hope of finding quantum gravity is the lack of any experimental clue, direct or indirect. This contrasts starkly with the manner in which copious phenomenological signatures had guided the quantum theories of other interactions, especially quantum electrodynamics. However, the universal belief is that a theory of quantum gravity exists and it is inevitable, waiting to be discovered. This conviction is the 'hypothesis of quantum gravity'.

Given this backdrop of strong theoretical conviction and relentless efforts of researchers during the past several decades, it will surely come as a crushing surprise if an unambiguous and direct experimental fact definitely refutes the hypothesis of quantum, gravity. The proof of refutation is simple and transparent.

2. The Refutation

If gravity is indeed quantized, gravitational waves consist of quanta associated with gravity, obeying the primary Planck-Einstein relations for quantized radiation, $E = h\nu$ and $p = h\nu/c$, where E

and p are the energy and momentum of one quantum, and ν is the frequency of a mode of radiation. The astrophysical gravitational waves that are routinely detected by the interferometric detectors like aLIGO and Virgo are in the range of frequencies 30 Hz to about 1000 Hz, corresponding to the range of energies $2 \times 10^{-32} - 6 \times 10^{-31}$ Joules per radiation quantum. These instruments detect gravitational waves by sensing minute synchronous oscillations of suspended mirror-mass elements of a Michelson interferometer of a length scale L, with signal enhancing cavities [9,10]. The differential gravitational strain ($\Delta L/L$), of less than 10^{-23} translates to an actual amplitude of 10^{-19} m for the oscillations of the mirror elements. (The actual detection metrology involves a feedback technique. However, the force balance implies the validity of the energy balance.) The astrophysical GW are 'chirped', progressively increasing in their amplitude and frequency until the last stage of a binary merger. If gravitational radiation is indeed quantized, the energy transferred from the waves to a mirror element will be $E = h\nu$, where $N(\nu)$ is an integer larger than or equal to 1. Averaged over a cycle, the energy in differential oscillations is then $\bar{E} = \bar{N}(\nu)h\bar{\nu}$.

The detected gravitational waves indicate a superposition of phase-coherent oscillatory components. Both the frequency and amplitude of the waves as well as the oscillatory response of the interferometer mirrors are progressively increasing. The cycle-averaged energy $\bar{E}_m$, of the oscillations of the mirrors of mass M at an average frequency ν, is

$$\bar{E}_m = 2\pi^2 M A^2 \nu^2 \tag{1}$$

From the elementary physics of quantized radiation, this implies that the average number $\bar{N}$ of quanta involved in such coherent state of gravitational quanta is much larger than 1 ($\bar{N} \gg 1$). Only then $1/\sqrt{N} \ll 1$, a condition that is required to have a relatively well defined phase while an observable signal is being detected [11,12]. In fact, the requirement that the two end-mirrors of the Michelson interferometer, separated by a diagonal distance of about 5.7 km should oscillate in opposite phases, in response to a passing quadrupolar gravitational wave, is a strong constraint that demands $\bar{N} \gg 1$.

For the special case of gravity, there is a more stringent constraint imposed by the equivalence principle. The amplitude and phase of the oscillations of all mass elements have to be locally identical and independent of their mass or internal structure. Only then the local gravitational accelerations of all bodies are identical at all times, making any differential motion locally undetectable. This is why the GW detectors are designed to measure differential oscillations of spatially well separated mirrors. One can easily see that the mean number of quanta involved in the oscillations of the mirrors should be large enough ($1/\sqrt{N} \ll 1$) to avoid observable probabilistic statistical variations between different mass elements locally. This requirement is reinforced by the fact that the actual detection involves coincident and phase-synchronised sensing by independent detectors separated by thousands of kilometres. This is impossible when the average number of quanta absorbed is of the order of one, which is entirely probabilistic owing to the characteristic indeterministic nature of quantum mechanics. The Equivalence Principle dictates that the cross section for the transfer of any gravitational quanta is strictly proportional to the mass of a suspended body, and that no fraction of that energy is partitioned into material dependent internal degrees of freedom. Only then the local oscillatory amplitudes of all mass elements in a small spatial region can be identical, as evident from the expression for the mean energy of oscillation, $\bar{E}_m = 2\pi^2 m A^2 \nu^2$. Thus, not only that the average energy in the differential oscillations strictly cannot be smaller than $E = h\nu$, it should also be such that $\bar{N} \gg 1$ for a phase-coherent signal to be detected.

Now I make the vital observation that the typical average energy in the kinetic motion of detector mirrors from astrophysical gravitational waves is less than the energy corresponding to even a single radiation quantum! This is of course physically impossible if gravity is quantized. This startling fact, hitherto unnoticed, immediately provides the first decisive test of the hypothesis of quantum gravity.

From the fundamental constraint of energy conservation, the average energy $\bar{E}_q$ transferred as the quanta of gravitational radiation at frequency ν equals the average motional energy $\bar{E}_m$ in the

oscillatory response of the mirrors, with an average amplitude A. For a mirror of mass mM in a terrestrial interferometric detector, the average energy in its oscillations at a mean frequency μ is

$$2\pi^2 M A^2 \nu^2 = \bar{N} h \nu \tag{2}$$

Therefore,

$$\bar{N} = 2\pi^2 M A^2 \nu / h \tag{3}$$

The GW strain sensitivity is lower than 10^{-23} from about 40 Hz, corresponding to a differential amplitude of oscillation less than 10^{-19} m. The sensitivity achieved at 100 Hz in the recent O4 observing run is about 6×10^{-24}, which translates to a differential oscillation with an amplitude less than 4×10^{-20} m [13]. Considering $\nu \approx 100$ Hz, and $m \approx 40$ kg, we get in a conservative calculation that $\bar{N}(\nu) < 0.2$. In fact, throughout an active operating range of 30–600 Hz, where most events are detected, $\bar{N} < 1$. This is an impossible physical situation if the gravitational radiation consists of gravitational quanta, requiring that the exchange of energy in gravitational phenomena occurs through the exchange of a finite number of quanta. This transparent result contradicts decisively the fundamental tenet of quantized gravity. Thus, we have direct experimental evidence that the energy transfer in the detection of coherent gravitational waves in the operating interferometric detectors definitely falsifies the hypothesis of quantum gravity.

I reiterate the vital point that in all terrestrial interferometric detections of gravitational waves, without exception, the average energy in the response of the detector mass elements is far less than the energy of a radiation quantum at the relevant frequency, which is physically impossible if the hypothesis of quantum gravity is correct. Another way of expressing the strict fundamental constraint of quantization is to write it in terms of *the quantized amplitude $A(\nu)$* of the response of a detector, corresponding to the number of quanta (N) driving the response. From equation 2,

$$A(\nu) = \sqrt{\hbar/\pi M\nu} > 10^{-18}/\sqrt{\nu} \tag{4}$$

Thus, in the range 40-100 Hz, the minimum quantum gravitational amplitude is larger than 10^{-19} m. The actual detections violate this constraint.

The discrepancy that is unambiguously revealed by the refuting direct experimental evidence is in the most elementary and essential signature expected in quantum gravity– the Planck-Einstein quantization of gravitational radiation and its manifestation in all phenomena involving an exchange of its energy. Ironically, the same considerations that revealed the nature of quantization in electromagnetism more than a century ago have now provided a refuting test of the long-cherished hypothesis of a similar quantization in gravity.

3. Additional Considerations

The quantitative conflict and the strength of evidence will enlarge in the near future, when the sensitivity of the interferometric detectors will be improved by a factor 2 or 3. Then, we will see that $\bar{N} \leq 0.1$, which will leave no conceivable margin for a resurrection of quantum gravity. There is another important side to this fact, that the oscillatory response of mirrors in a GW detector involves an average energy that is much less than the energy of a single gravitational quantum. As discussed already, *quantization implies that there is an absolute minimum amplitude for the response at a particular frequency*, $A_m(\nu) = \sqrt{\hbar/\pi M\nu}$. Since the sensitivity of the operating GW detectors is already below this level in the frequency range 50–500 Hz, there would have been no significant advantage to be gained, except a larger signal to noise ratio, from increasing the sensitivity in this frequency range, if gravity were indeed quantized. Most significantly, much of the plans for upgrades and next generation detectors would be misguided in a scenario where gravity is quantized, because no detection can be with a strain amplitude $\Delta L(\nu)$ lower than the minimum amplitude $A_m(\nu)$. For example, the single quantum limit on the amplitude at 20-1000 Hz will be well-surpassed by the A# design upgrade of the

operating aLIGO detectors [14]. The probability for the exchange of a quantum depends only on the mass of the suspended mirror, and not on the measurement sensitivity achieved. Therefore, the next generation GW detectors like the Cosmic Explorer and Einstein Telescope will not add significantly to the number of detections in this frequency range, *in a scenario where gravity is quantized*. (However, the expansion to the low frequency range of 5–20 Hz is very important, targeting low mass black holes at large distances.) *Their operation at the improved sensitivity is conditional on the possibility that the energy of oscillations of mass elements can be much smaller than the energy of a single gravitational quantum.* In other words, the very relevance of next generation GW detectors, as superior instruments in the low frequency region, depends crucially on the falsity of quantum gravity.

Another important aspect in the detection of GW events, under the hypothesis of quantum gravity, concerns a saturation effect in distance estimates. For classical gravitational waves, the distance of an event is estimated by the detailed matching of the amplitude of the tidal strain with the templates of frequency-amplitude characteristics of the waveform in the event [11]. In a scenario of quantum gravity, any detection should involve at least a single gravitational quantum. At this level, the detection (of a signal induced by a gravitational quantum) becomes probabilistic. Therefore, when this limit is reached, one cannot any more discern the distance at which the event has occurred. All these signatures strengthen the confidence in the direct experimental evidence that refutes the hypothesis of quantum gravity.

4. Summary

I have proved from a direct and transparent experimental evidence that the hypothesis of quantum gravity is false. The average energy in the oscillatory response of operating GW detectors to astrophysical gravitational waves, in the low frequency range of 40-100 Hz, is definitely smaller than the energy of even a single gravitational quantum. This is physically impossible if gravity is quantized, with the essential consequence that such quantization is reflected in its radiation sector through the characteristic Planck-Einstein relations for the quantization of GW radiation, $E = Nh\nu$. This fact definitely falsifies the hypothesis of quantum gravity. The phenomenon of gravitation is not subject to the non-deterministic laws of quantum mechanics. The strength of the proof is its simplicity and the clear quantitative margin that cannot be mitigated by small corrections or alterations in the fundamental premises. The proof can be denied only by denying the quantization of the radiation sector of gravity, or by arbitrarily hypothesising a much smaller quantization fundamental constant that is specific to gravity, which amounts to the denial of universal quantum mechanics itself.

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