# Novel Insights into Nonlocal Gravity

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Our various experiments, analyses and theoretical models to describe anomalous phenomena related to so many diverse physical systems like superconductors, capacitors and others led us to consolidate the idea that all existing particles are in a preexisting state of quantum entanglement. Such a generality involving weight reduction of the devices leads us to inevitably infer a direct relationship between such a state and gravity, considering it as a nonlocal force. In this work, we intend to explore this issue of generality and then propose, on the basis of such a theoretical framework of generalized quantum entanglement state, to investigate in this alternative way other issues such as the small order of magnitude of the gravitational force in relation to other known local forces, as the electromagnetic one, explain why the gravitational force is attractive in the Universe and why particles and bodies are limited to the speed of light in the vacuum even interacting through instantaneous interactions. We also explore the issue of quantum interference in neutron experiments as being induced by nonlocal gravity.

## 1 Introduction

One of most important topics of research in physics relates to the nature of the gravitational field, mainly considering that the quantum mechanics cannot describe the physics in the macroscopic and even astronomical scale, in which the gravity force is the prominent one. In Quantum Field Theory, it is well known that the fundamental interactions of Nature in the nuclear and atomic scale are possible through gauge bosons. In the nuclear medium, gluons are the gauge bosons of the weak and strong interactions. Further, in our macroscopic world, the electromagnetic forces are dominant and the interactions between bodies are mediated by photons. However, despite the proposal of the graviton as the gauge boson for gravity, till now, no evidence of its existence has been found, so that it becomes hard to obtain a theoretical framework that encloses all the interactions in Nature and as consequence a unified theory of fields, although a series of alternative theories [1–4], interpretations [3, 4] and unification theories have been proposed in literature [5, 6].

Although such investigations are very hard to be successful, many physicists have tried alternative theoretical explanations for understanding the nature of gravity and beyond. As examples, we can cite

- the Emergent Gravity theory [7];
- the possibility of a fractal physical space-time [8];
- the existence of the coupling between it and electromagnetism or the hypothesis that considers gravity as derived from the electromagnetic interaction [9];
- the idea from which relevant information on the emergence of space is hidden at the quark / hadron level, by following the line of thought from which space is an attribute of matter [10], so that quantum properties of matter or the discretization of mass induces us to believe in some form of quantization of space, with intrinsic consequences to gravity.

In this context, it is natural to suppose that quantum mechanisms could really be responsible for generating the gravitational force. The possibility that the collapse of the wave function in quantum mechanics is not merely a mathematical formalism but a real physical effect and ultimately connected to classical gravity has been discussed a long time ago since the proposal of the Diósi-Penrose model (DP) [11–14]. The idea was first conceived by Diósi in the study of the influence of gravitational fluctuations on quantum systems. Next, Penrose reported an estimation for the collapse time of a superposition due to gravitational effects that was the same found by the precise dynamical equation given by Diósi, based on the idea of a noise-based dynamical reduction effect. Such a topic has been still explored up to recently [15].

Another relevant idea on the local action of gravity refers to the inclusion of quantum fluctuations effect, which is a nonlocal component in the description of cosmological physical systems. For instance, in [16] such a point is analyzed by assuming that a mass scale is dynamically generated in the infrared regime, giving rise to nonlocal terms in the quantum effective action of gravity. Hence, the associated nonlocal gravity models are analyzed in many conceptual aspects as causality, degrees of freedom and their cosmological consequences. In a recent work [17], we have an overview on many aspects of nonlocal gravity cosmology.

On the basis of such previous ideas, we think that the hypothesis of generalized quantum entanglements (GQE) that we have developed in some previous works [18–22] could be a candidate for understanding some aspects and properties related to gravity, mainly considering the recent report of the existence of a type of quantum force [23]. In addition, in another work [24], it was asserted that it would be possible to infer entanglement gravitational generation by using an atom interferometer [24]. The basic idea consists in the hypothesis that if we suppose gravitational perturbations as being quantized into gravitons, then the resulting graviton interactions should lead to an entangling interaction between massive bodies. However, the authors proposal of an experimental test – introducing the concept of interactive quantum information sensing – was not robust as reported and an erratum was published [25] with basis on the calculations showed in [26]. Basically, in [26], the authors showed by means of an explicit example that an interaction between a harmonic oscillator and a two-level test mass mediated by a local operation and classical communication channel produces a signature that in [24] was claimed to be exclusively for transmitting quantum information. Although the result was not really highly robust, in [25] they suggest methods to overcome the weakness in the proposed experiment. So, with basis on [23] and [25], we see that the subject is really intriguing and motivating in the sense of investigating and deepening the possibility, consequences and implications of associating generalized states of quantum entanglement between microscopic particles and the gravitational force. Although preserving quantum entanglements effects over macroscopic scale [27] is very difficult due to physical interactions, in many specific situations, as for instance in cases of physical systems subjected to high magnetic fields (in which the spins of all the component particles point in the same direction), effects of such a quantum state can be experimentally verified [28–30]. In addition, it is also proposed in [27] a physically robust quantum entanglement process that indicates the persistence of such states to classical scales.

From the general lines that we here exposed, it is our proposal in this work to discuss a generality of ideas that corroborate for this line of thought and research, in order to motivate investigations on the area. In more specific terms, we intend to describe at least four relevant lines of work concerning such aspects. One of them refers to a work in which the expansion of the electromagnetic field in a power series indicates that relevant terms of the series are equal to a purely gravitational term. Further we discuss how such an approach can be improved so that quantum entanglements among all the particles in the system can induce the force of gravity. In another study, we discuss some relations between the gravity and quantum mechanisms, that is, that the speed of light in the vacuum is a limit to the matter as a consequence of its origin (quantum fluctuations of the vacuum) and the interferences on beams of neutrons by gravity. At last, we discuss the description of the nonlocal gravity proposal by adopting the GQE hypothesis.

## 2 Generality of gravity

In the early 1990s, one of the authors of this manuscript began studies in order to investigate possible effects of quantum entanglements in the macroscopic environment, starting from the premise that all existing particles in the Universe are in a preexisting state of maximum quantum entanglement, considering that at their origin (Big Bang) they were all in causal contact in a very small volume and associating such a collective state with gravity and inertia [18]. At first, one could imagine that this would contradict the concept of quantum monogamy [31], in which is reported that the concept is related to the idea that an entangled state cannot be shared with many parties, that is, the more parties, the less entanglement occurs among them. However, in reality, such a property is valid considering that two particles are entangled with each other, but not with a third or others, so that when the entanglement spreads the state of maximum entanglement is no longer possible. In the model that we consider, all particles are already entangled with each other since the beginning of the Universe.

The generality of both the gravity and the preexisting collective quantum state that governs all particles is one of the main factors that they can be somehow related to each other. Here generality means that the interaction involves all existing particles. For instance, electromagnetism involves only the charged particles and does not present such a characteristic.

Using the quantum mechanics formalism [18], it was verified that the dynamics of particles can be governed by nonlocal potentials in addition to the local ones and that, therefore, there is a possibility that gravitational potentials are also nonlocal due to other existing evidences described in this paper. A recent work [19] showed in an experiment that there was a correlation between the polarization of electric dipoles and photons (without local interaction between them) via discrete observables and indicated the possible preexistence of generalized quantum entanglements (we will call it GQE or the GQE model from now on). Penrose [32] reported that the evolution of states indicated by the Schrödinger equation inevitably makes all particles entangled and other studies [33] have also indicated that quantum entanglements can exist even in particles that never coexisted, considering entanglement chains. A very interesting work that we will analyze further here by Buniy and Hsu [34] indicated that everything in the Universe is maximally entangled despite not associating this property with gravity. The main argument is that particles had causal contact at the beginning of the Universe and with its expansion, the vast majority of current entanglements occur between particles that are beyond the causal horizon and that must be uniformly distributed in thermodynamic equilibrium (as evidenced by cosmic radiation). Such entanglements cannot even be removed by local interactions. One of the consequences of degrees of freedom being beyond the causal horizon is that two particles or two groups composed of a few particles, called X and Y, chosen at random, are not likely directly entangled with each other. This is because in this condition, the vast majority of degrees of freedom are not contained between the two subsystems X and Y, but outside them (causal horizon that involves both). Therefore, for this reason the two subsystems share a negligible entanglement with each other.

In order to formalize the analysis, one can describe the system by the equation

$$\rho_{XY} = \sum_i \omega_i \rho_X^i \otimes \rho_Y^i , \tag{1}$$

which shows the density matrix that describes the entanglement between the two subsystems, each of them described by its individual density matrix.

Both of the subsystems are casually connected and separated. Now if the subsystems X (small subsystem) and Y (rest of the Universe with large amount of particles) are separated by the causal horizon (space-like separated) so that the vast majority of degrees of freedom are contained between both, we have that the density matrix describes the entanglement between both subsystems as described in equation

$$\rho_{XY} = \sum_i \omega_i \mid \phi_{XY}^i \rangle\langle \phi_{XY}^i \mid , \tag{2}$$

in which the term $\phi_{XY}^i$ represents a pure state and $\omega_i$ are probabilities.

In the situation formalized by (2), unlike the previous situation formalized by (1), the two systems X and Y share a high degree of entanglement. Fig. 1 summarizes the two situations analyzed here about entanglement across causal horizons. On the left side we have the X and Y subsystems with few particles surrounded by the causal horizon (crosshatched background) where mutual entanglement is negligible. On the right side we have the subsystem X with few particles surrounded by the causal horizon (crosshatched background) smaller than the subsystem Y which contains the rest of the Universe (a myriad of particles) where mutual entanglement is immense.

It is notable that the degree of entanglement between such subsystems depends directly on their dimensionality in the correspondent Hilbert space with respect to the dimensionality of the causal horizon and that these grow exponentially according to the number of degrees of freedom they have, that is, with the amount of particles that constitute them and their possible states. This indicates that it is possible to make local manipulations of a myriad of particles so that the effects of entanglements between subsystems become detectable, that is, for local systems to pass from the condition indicated by (1) and diagram on the left side of Fig. 1 to the one indicated by (2) and the right side of Fig. 1.

That's what we actually performed in our previous experiments [20, 22, 35, 36]. In various experiments we polarized a myriad of electric dipoles inside a dielectric under intense electric fields, magnetized a myriad of magnetic dipoles inside solenoids under intense magnetic fields, placed a myriad of electric and magnetic dipoles in collective precession

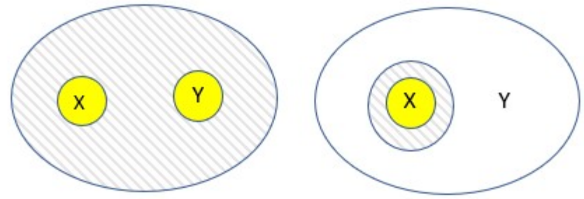


Fig. 1: Scheme of entanglement accross horizons. At left, we see the systems X and Y with negligible amount of entanglement between them because their small areas (extremely small quantity of particles) compared to the area of the causal horizon (crosshatched background). At right, we see the opposite, the big amount of mutual entanglement between the systems X and Y, considering the big value of the sum of their areas (myriad of particles) compared to the small area of the causal horizon (crosshatched background).

and mobilized a myriad of charge carriers within conductors, superconductors and semiconductors. Considering only the nonlocal interaction between two separate simple dipoles and no local interaction via known forces as shown in Fig. 2, we have that the action of a local potential (magnetic or electric) in one of the dipoles affects the other dipole of the pair that is in the environment. The state of the pair of dipoles can be represented as being typically entangled [28] as represented by equations

$$\mid \Psi_1 \rangle = \frac{\mid 01 \rangle - \mid 10 \rangle}{\sqrt{2}} \tag{3}$$

and

$$\mid \Psi_2 \rangle = \frac{\mid 01 \rangle + \mid 10 \rangle}{\sqrt{2}} , \tag{4}$$

in which the state zero means orientation along the field and the state one means orientation against the field. These kets represent entangled states of a pair of dipoles in which one of them is oriented by a local field.

The nonlocal connection between the dipoles explains the supposedly anomalous forces in the form of weight variation that are measured in devices where high local potentials are applied and also in forces that such devices induce at a distance. Such inductions cannot be blocked as we have seen in our experiments [20, 22] because in fact there are no isolated systems and this is precisely one of the main properties of gravity.

We deal in our experiments with intense local potentials that have driven myriads of particles, but immense amounts of particles in the Universe are affected by local bound potentials of very weak magnitude so that nonlocal net effects are extremely weak, but we will show later in this work that these may explain the weakness of gravity through the other known forces.

A gravitational-like interaction was detected in our experiments in [20], where a shielded capacitor via Faraday cage

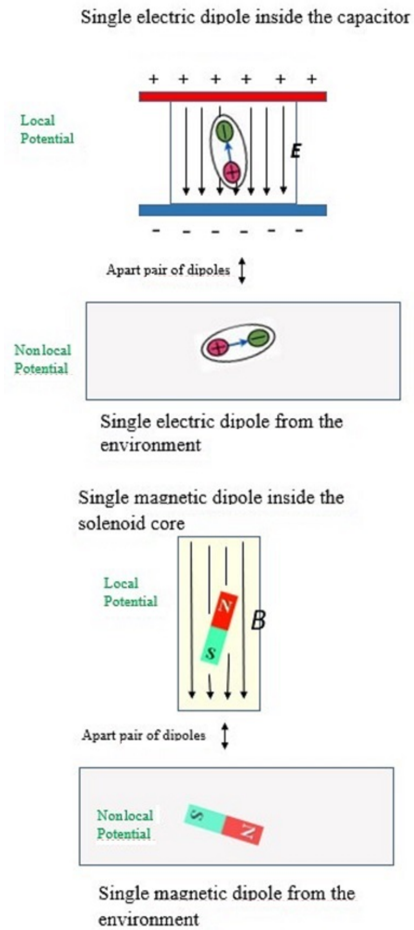


Fig. 2: Simplified analysis of the nonlocal interaction dipole-dipole.

enclosed inside a box was subject to a high voltage applied via shielded and insulated wires. Its weight variation cannot be explained via ionic winds and local interactions such as electrostatic, magnetic or acoustic ones.

The adoption of macroscopic observables as witnesses of entanglement of systems composed of many particles such as the electrical susceptibility $\chi_e$ and the magnetic susceptibility $\chi_m$ provides the necessary tools that can be applied in theoretical formalisms that explain the experimental results [21, 29, 30] considering the complexity involving quantum systems composed of myriads of particles. According to [29], the entanglement witness is shown as being more general (in the sense that it is not only valid for special materials), associating some macroscopic observables such as magnetic susceptibility $\chi_m$ with spin entanglement between individual constituents of a solid. It was proposed in [29] a macroscopic quantum complementary relation basically between magnetization $M$, representing local properties, and magnetic susceptibility $\chi_m$, representing nonlocal properties. By defining for a system of $N$ spins of an arbitrary spin length $s$ in a lattice the quantities:

$$G_l = 1 - \frac{kT\overline{\chi}}{N_s} \tag{5}$$

and

$$G_{nl} = \frac{\langle \vec{M} \rangle^2}{N^2 s^2}\,, \tag{6}$$

in which $M$ is the modulus of the magnetization vector, $k$ is the Boltzmann constant, $T$ the temperature and the susceptibility of the system is defined as

$$\overline{\chi} = \chi_x + \chi_y + \chi_z\,, \tag{7}$$

hence, it was shown in [29] that one has:

$$G_l + G_{nl} \leq 1\,. \tag{8}$$

Such quantities have specific meanings, that is, $G_{nl}$ represents the quantum correlations between the spins in the solid (nonlocal properties) and $G_l$ represents the local properties of individual spins. The hypothesis of preexisting GQE indicates that there are no isolated systems as mentioned before, thus the magnetic core and the environment around it are both part of the same system where the inequality (8) can be considered accordingly. In other words, if one quantity increases then the corresponding counterpart quantity has to decrease. If $G_l$ increases and $G_{nl}$ decreases in the magnetic core, $G_{nl}$ decreases and $G_l$ increases in the environment and vice-versa. This is the same framework described before involving a simple system with two entangled magnetic dipoles. If we increase the intensity of a magnetic field ($G_l$) applied in one then the nonlocal forces ($G_{nl}$) must increase in the other.

Then, calculating the intensity of the nonlocal force $F$ generated by a series of magnetic spins (dipoles) within the core of solenoid subjected to intense magnetic fields through classical quantities such as the magnetic susceptibility of the solenoid material (macroscopic observable) and the magnetization $M$ can be defined by

$$F = \frac{1}{16\pi^2}\frac{SBI}{\theta}\,. \tag{9}$$

The product $SBI$ represents the summation of the energy eigenstates of the internal spins (dipoles) of the solenoid, in which $S$ is the area of the solenoid, $B$ is the internal density of magnetic flux and $I$ is the electric current that flows through the wires of the solenoid and which generates the magnetic field applied. The number in the denominator comes from the Planck constant $\hbar$ squared existing in the Hamiltonian of the spin system and $\theta$ is the radius of the cylindrical solenoid. Such an equation corroborated the experimental results of experiments with magnetic solenoids.

Another experiment replicating Galileo's experiment in the Tower of Pisa and referring to spins or magnetic dipoles is related to locked magnets [37]. The experiments showed that in free fall two strong magnets in repulsion coupled fall more slowly than equivalent ordinary (demagnetized) objects and two strong attractive magnets coupled to each other fall faster than demagnetized equivalent objects. In the GQE model, the phenomenon of difference of gravitational acceleration can be explained in a consistent way [37]. The theoretical predictions using such a formalism are corroborated by the results of the experiments and following the same criterion of using macroscopic quantum observables (considered as classical quantities) representing the entanglement of a myriad of particles with the environment, so that it was possible to build models that explain other systems such as dipole electrical charges in dielectrics and electrical charges flowing inside conductors, semiconductors and superconductors. It is known that light beams are deflected and distorted (gravitational lensing) by gravitational fields of massive bodies and considering such phenomena we performed experiments with isolated piezoelectric materials that also showed deformed laser beams effects [35]. This indicates another possible association of the GQE model with gravity.

Another experiment [38, 39] demonstrating force induction at a distance with gravitational characteristics was carried out involving the mechanical displacement of masses of different materials in a pendulum caused by collimated impulses produced by a superconductor subjected to high voltages. An explanation via the Theory of Relativity was proposed in [40]. Our GQE model [21] can also explain that effect in a consistent way with the experimental data, especially the relationship of applied energy and the mechanical energy of oscillation of the pendulum. All this argument possibly demonstrates the generality of both gravity and GQE and that both have a very close relationship with each other. Further we conclude that there is an intrinsic connection between these physical entities that affect all bodies and particles (fermions and bosons), regardless of their constitution.

## 3 The order of magnitude of gravity

According to GQE, all the particles transfer variations of moment indistinctly among them, considering as basic hypothesis that they are quantically entangled and subjected to known nonlocal forces. Let us assume valid GQE hypothesis and investigate if quantum mechanisms like that can explain the gravity force. The question to be answered is: *But how to explain that the gravity force can be originated from such momenta exchange if it is extremely weak and the magnitudes of the local forces are much higher?* For instance, the gravitational force is $10^{-36}$ times smaller than the electrostatic force at the same distance [9].

In general, all the local forces such as the electromagnetic one, weak nuclear and strong nuclear forces are attractive and repulsive [41], but what explains the fact that only the gravitational force is attractive? In [9], a very interesting study was reported by Assis, indicating that two neutral electric dipoles where negative charges oscillate with small angular velocity around an equilibrium position can attract each other through an average net electrostatic force that falls off as the inverse square of the distance between them and whose magnitude are compatible with that of the gravitational force. Besides he also showed that the same behavior is valid for groups of $N$ dipoles; in other words, he showed that in that theoretical framework gravitation can be derived from electromagnetism. To reach this result, Assis used calculations based on Weber's generalized potential energy shown by equation

$$U = \frac{q_1 q_2}{4\pi\epsilon_0}\frac{1}{r_{12}}\left[1-\alpha\left(\frac{\dot{r}_{12}}{c}\right)^2-\beta\left(\frac{\dot{r}_{12}}{c}\right)^4-\gamma\left(\frac{\dot{r}_{12}}{c}\right)^6-...\right], \quad (10)$$

considering dipole oscillations in the three $x$, $y$ and $z$ directions. Eq. (10) indicates the dependence of the potential energy between the dipoles in terms of the power series in parentheses, in which $r_{12}$ is the average distance between the two particles of the dipole and $\alpha$, $\beta$ and $\gamma$ are the parameters that indicate the magnitude of those power series terms. As known, $q_1$ and $q_2$ are the oscillating negative charges of the dipoles, $\epsilon_0$ is the vacuum permitivitty and $c$ is the speed of light. The dot in the distance $r_{12}$ is the notation used for the time variation of the distance between the two charges of the dipole.

The force between the dipoles is attractive and given by

$$\vec{F}_{12} = -\hat{r}_{12}\frac{dU}{dr_{12}}\,. \quad (11)$$

Eq. (11) indicates the force between two dipoles 1 and 2 apart by the distance $r_{12}$ and its attractive feature.

Surprisingly, the calculations resulted in a cancellation of the most significant terms of the series so that the potential energy – and, therefore, also the force – started to decay according to $c^{-4}$ reproducing Newtonian gravitation as being the fourth-order of the electromagnetic effect.

Considering the values of the charges equal to the electron charge, that is, $q_1 = q_2 = e$, and making $A_1 \sim 10^{-10}$ m, which is the typical size of the atom or molecule where the electrons are vibrating around the positive nucleus; and also considering equal the angular velocities of the oscillating charges of the dipoles $\omega_1 = \omega_2 = \omega$ and the coefficient $\beta = 1/8$, from (10) Assis interestingly simulated Newtonian gravitation with electromagnetism demonstrating an interesting relationship between electromagnetic parameters, as shown in the left term of equation:

$$\frac{7}{18}\frac{1}{8}\frac{e^2}{4\pi\epsilon_0}\frac{A_1^4-\omega^4}{c^4} = GM^2\,, \quad (12)$$

as gravitational parameters shown in the term on the right, where $G$ is the usual gravitational constant and $M$ is the mass of the neutron or the mass of the hydrogen atom.

Assis also indicated other issues in his model, such as the relationship of inertia with gravity derived from electromagnetism that we will address in future works. In addition, he also indicated possible limitations such as the fact that the calculations do not include relativistic corrections, as proposed by Phipps [42] for Weber's generalized potential energy. The model here investigated can explain the orders of magnitude of the gravitational interaction, its decay with the distance between the bodies and also its attractiveness characteristic through electromagnetic interactions between neutral dipoles, more specifically between the charged particles that compose them such as electrons. Despite the apparent success of this model, if we are supposed to isolate such dipoles through electromagnetic shields (Faraday cages) we could suppress them and it is known that in principle there is no gravitational shielding. In other words, there is an apparent paradox if we adopt such a model for gravity. Another issue is that electromagnetic interactions between electrically charged particles such as electrons and protons that make up neutral dipoles were considered to derive the gravitational interaction, but it is known that neutral particles such as photons and neutrinos (it is assumed that the latter can contribute most of the mass of the Universe) undergo the action of gravity. So, these arguments lead us to conclude that a very important feature must be added to the model studied here in order to derive gravity from local forces, which is to consider the GQE hypothesis. Thus, a potential energy such as Weber's generalized one given by (10) can be considered as a local potential energy $V$ in the Hamiltonian $\hat{H}$ of a multiparticle system represented by (18) that we discuss in more detail in section 5. Such a local potential can provide the interaction with particles external to the system through nonlocal forces that we can consider to be gravitational.

Our previous work [43–45] has corroborated that such nonlocal forces can indeed be induced and measured externally when, for example, strong electric fields are applied locally to a myriad of atomic and molecular dipoles contained in dielectrics even though they are shielded by a Faraday cage. In the model here discussed and represented by (10), we assume local potentials between dipoles. Assis indicated in [9] that terms lower than fourth-order are cancelled and are preponderant in the Universe groups of particles that interact with each other or particles that interact with themselves (for example, when a neutrino splits into two virtual particles and then the virtual particles become a neutrino again). This phenomenon occurs via electromagnetism but also via other known local forces.

To validate such a model, it is necessary to use a quantum approach as done with London dispersion forces [46] and also a relativistic approach.

## 4 The quantum origin of the speed of light

Quantum mechanics successfully demonstrates that particle dynamics have a dual nature where the mutual transfer of momentum is governed both by local interactions mediated by force-carrying particles such as the photon in the case of electromagnetism and by nonlocal interactions arising from entangled quantum states between particles. In the first case, the interaction speed follows a finite upper limit and in the second case the interaction is instantaneous. Another fundamental feature of the theory of relativity is that the speed of light is independent of any source or reference, although a proposal to challenge such physical property has already been done in the literature [47]. Knowing the origin of the finite limiting velocity of local interactions, more specifically the speed of light, is critical because both special relativity and general relativity are built on this fundamental characteristic. A very interesting work by Urban and his collaborators [48] proposes to derive the speed of light from quantum mechanics. The model in question treats the velocity of the real photon as being instantaneous as well as with nonlocal interactions, but its propagation through the quantum vacuum occurs in leaps like those of a frog. It "jumps" instantaneously between the pairs of virtual particles of ephemeral duration being absorbed and re-emitted in a chain. The delay inherent in the absorption and re-emission process is what determines the finite propagation velocity $c$ of the photon. Electromagnetic properties such as permeability $\mu_0$ and permittivity $\epsilon_0$ of the vacuum are determined by the creation and destruction of ephemeral particles such as electrons and positrons in addition to other fermions, and therefore both statistically determine on average the speed of light in the vacuum, given that

$$c = \frac{1}{\sqrt{\mu_0 \, \epsilon_0}}\,, \tag{13}$$

allowing some small variation to be confirmed experimentally. Einstein [49, 50] showed that the total mass $m$ of a body is the measure of its energy content $E$ (mass-energy equivalence) according to the relation $E = mc^2$, where $c$ is the speed of light in vacuum. In order to reach this conclusion, he considered that the body yielded or absorbed energy in the form of electromagnetic radiation and that such an action caused its mass to change. So the exchange of force carriers like photons that are constrained in their propagation speed due to their interactions with the ubiquitous quantum vacuum that surrounds all bodies and particles appears to be a crucial factor for both special and general relativity, both experimentally validated.

A pioneering experiment among the various later experiments that validated such theories was the Hafele-Keating one [51] in the 1970s, which compared the measurements of time between precision atomic clocks inside an airplane that spent a certain time at high altitude and speed synchronized with others that were at rest on land. After the plane landed, the measurements of the clocks were compared and showed to be in notable disagreement with each other, obtaining an accuracy above 98% in relation to the theoretical predictions [52, 53] given that the clocks on board suffered an advance in the proper time due to the fact that they were at a higher altitude, that is, subject to a weaker gravitational potential energy than at the surface, corroborating the relationship between proper time $d\tau_1$ (plane) and $dt$ (surface) indicated in (14) derived from general relativity (Schwarzschild metric):

$$d\tau_1 = \sqrt{1 - \frac{2m}{R}}\, dt\,. \qquad (14)$$

The clocks were also delayed due to the effect of special relativity with the plane's speed $v$, corroborating the relationship between the proper time $d\tau_2$ (plane) and $dt$ (plane at rest on the ground) indicated in (15):

$$d\tau_2 = \sqrt{1 - \frac{v^2}{c^2}}\, dt\,. \qquad (15)$$

In (14), $R$ indicates the distance from the planet's center of mass (altitude) and $m$ represents the relativistic mass of the planet according to the relationship $m = GM/c^2$, where $G$ is the usual Newtonian gravitational constant and $M$ is the planet's rest mass. The theory of relativity also predicts other effects [52, 53] such as the advanced perihelion of the planets, the deflection of light by the gravitational field and the spectral displacement of gravitational origin, all of which are experimentally proven. According to GQE theory, all particles are quantum entangled and, therefore, interact not locally instantaneously, but due to the fact that they also interact via local interactions mediated by force carriers limited to the velocity $c$ taking into account their delayed propagation, through the ubiquitous quantum vacuum, the predictions of both general and special relativity support under certain conditions part of phenomena such as those mentioned above that Newtonian physics cannot explain.

The understanding of such "complementarity" in the coexistence of nonlocal and local interactions is analogous to what exists in the corpuscular and wave aspects because they seem contradictory, but are actually complementary according to quantum mechanics. Therefore, it is essential to study certain aspects of contradictory phenomena in relation to general relativity and special relativity, as indicated by van Flandern [54]. For example, according to him, the photons emitted by the Sun arrive at planet Earth 8.3 minutes after being emitted, time in which the Sun moves 20 arcs of a second in relation to the terrestrial reference. This causes the classic optical aberration studied by Bradley in 1728 to occur [54]. If such a phenomenon of aberration occurred with gravity, there would be a slight radial decrease in the intensity of the force so that the radial distance of the Earth's orbit would increase by 150 million kilometers every 1200 years, which in fact does not occur. Such an effect occurs with the radiation emitted by the Sun absorbed by dust particles where a transverse component affects their orbits (Poynting-Robertson effect). It is clear in this example the need to understand the complementary nature in which the gravitational interaction is instantaneous as proposed by the GQE theory and that the optical aberration in the radiation emitted by the Sun occurs due to the photons having a finite propagation speed like the other force carriers. More examples are given by van Flandern such as the fact that gravity and light do not act in parallel directions, anomalies that occur during solar eclipses, *etc*. Other works such as [55] tried to answer why there is no aberration of gravity via General Relativity Theory without superluminal propagation of gravity assuming an approximation that the Sun and Earth have a mutual uniform motion. On the other hand, other works report possible superluminal different phenomena such as superluminal photonics tunneling [56] and superluminal X-rays [57]. Regarding the gravity waves with approximately the speed of light that were supposedly detected by the huge laser beam interferometers of LIGO-VIRGO collaboration, it must be necessary to investigate deeply as the authors [58] are proceeding in order to explain if the deviation of the beams was produced by other physical effects such as propagating vacuum flutuations caused by huge cosmological events or by another local events. There is another experiment that supposedly evidences the nonlocal nature of gravity in [39], in which is reported the generation of a supposed gravitational-type interaction using superconductors under high-voltage discharges carried out, where impulses of up to 70 ns were induced at a distance at an apparently superluminar velocity (supposedly) 64 times the speed of light within the limitations of the equipment. The study of light interaction with gravity impulses and measurements of the speed of gravity impulses were also reported in [59].

Based on these promising analyses, the authors intend to continue the studies to deepen the understanding of the mentioned complementarity (local and nonlocal) of the interactions as well as to carry out new experiments involving the measurement of the velocity of the gravitational interaction. The authors also intend to publish another work containing important topics related to the association between inertia and gravity, the Mach principle and the principle of equivalence between gravitational mass and inertial mass.

## 5 Quantum interference via gravitation

The theory of Entropic Gravity or Emergent Gravity [7] proposes that gravity is not a fundamental interaction based on Quantum Field Theory, and therefore is not mediated by particles called force carriers such as gravitons. This characteristic is analogous to the GQE theory, which also proposes that gravity is not mediated by force carriers, but is the result of the transfer of momentum at a distance between particles that undergo the action of fundamental or canonical potential energies at their locations, considering that they are all in a preexisting state of generalized quantum entanglement. The theory of Entropic Gravity has had a lot of opposition [60–62], but in this work we want to describe one of the oppositions [63, 64] that emphasizes that such a theory is not consistent with the result of the pioneering experiment of gravitational induction of neutron phase shift [65]. In the aforementioned experiment that uses interferometry, a beam of neutrons with coherent quantum wave functions is split and separated into two beams that pass through different paths and are then recombined again to form an interference figure. The diagram in Fig. 3 shows one of the beams passing through positions A, B and D on a trajectory with higher altitude with respect to the $Z$ axis (vertical) and another beam passing through positions A, C and D on a trajectory with lower altitude. Point D indicates the interference region where the two beams recombine.

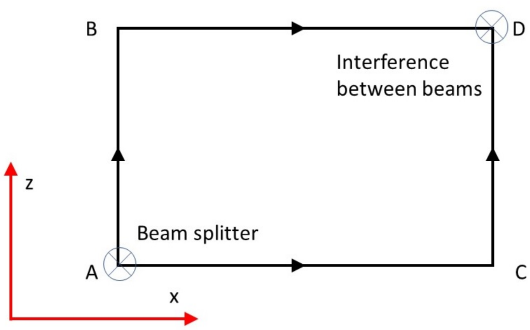


Fig. 3: Neutron interferometry experiment where a phase difference between the ABD and ACD beams was detected due to being subjected to different gravitational potentials [65].

The analysis of the interference figure clearly indicated that there was a phase difference depending on the neutron trajectory, related to the fact that the gravitational potential energy has a lower magnitude in the higher altitude trajectory (BD section) and higher magnitude in the lower altitude trajectory (CD section). The neutron momentum is therefore different on the trajectory ABD ($p_1 = \hbar k_{\rm BD}$), with respect to the momentum of the trajectory ACD ($p_2 = \hbar k_{\rm CD}$). The Schrödinger equation [66, 67]

$$-\frac{\hbar^2}{2m_n}\frac{\partial^2\Psi}{\partial z^2} + m_n g z\Psi = i\hbar\frac{\partial\Psi}{\partial t} \quad \text{for} \quad z > 0 \tag{16}$$

indicates dependence of the neutron dynamics on the gravitational potential energy represented by the term $m_n g z\Psi$ (the other term to the left of the equality represents the kinetic energy). The two terms to the left of the equality represent the standard Hamiltonian operator $\hat{H}$.

This Schrödinger equation (16) represents the dynamics of the neutron in the physical system described. The gravitational potential energy used in the formalism is that of classical physics, that is, it depends on the neutron mass $m_n$, the gravitational constant $g$ and the altitude $z$ ($Z$ axis) according to the term $m_n g z\Psi$. The predicted phase difference theoretically calculated according to the standard Hamiltonian $\hat{H}$ is consistent with the phase difference obtained experimentally.

But according to [63], in the case of entropic gravity, the interference pattern is destroyed because the gravitational interaction is not fundamental or canonical for this theory, that is, it behaves like a typical chaotic thermodynamic interaction so that the wave function of the neutron loses its coherence. In the theory of entropic gravity, the gradient of variation of the gravitational field with respect to altitude ($Z$ axis) is a statistical average of the thermal fluctuations involving a myriad of microstates. The last two terms in the equation

$$\hat{H} = \frac{\hat{p}^2}{2m} + V_{grav}(r) = -\frac{\partial^2}{\partial r^2} - 4\pi m\frac{\partial}{\partial r} - 4\pi^2 m^2 + mgr\,. \tag{17}$$

indicate deviation from the standard Hamiltonian and demonstrate that entropic gravity does not explain the experimentally measured phase difference. Eq. (17) shows the Hamiltonian operator according to the entropic gravity theory, where $m$ is the neutron mass and $r$ is the altitude value ($Z$ axis). In the experiment [65], according to the interpretation of the nonlocal gravitational interaction through the GQE theory, we can define the relevant Hamiltonian operator of the neutron-Earth system via equation

$$\hat{H} = -\frac{\hbar^2}{2}\left(\sum_{M=1}^{N}\frac{1}{M}\frac{\partial^2}{\partial z^2} + \frac{1}{m_n}\frac{\partial^2}{\partial z^2}\right) + \hat{V}_M\,. \tag{18}$$

which determines its dynamics in order to change the phase of its wave function coherently.

Eq. (18) shows the "standard" Hamiltonian operator of the nonlocal gravitational interaction of the neutron-Earth system according to GQE theory. The neutron moves on a trajectory with a certain kinetic energy (term on the right in parentheses in (18)) and in a state of quantum entanglement with the myriad of particles that make up the planet Earth whose total kinetic energy is represented in the sum of the term from the left in parentheses in (18). As the neutron is subject only to gravitational interaction with the planet Earth (its electromagnetic interaction is negligible because it has practically zero electric charge), the potential energy $\hat{V}_M$ (fundamental or canonical) inherent to the particles of the planet Earth is represented in (18).

The analysis performed here allows us to suppose that the phase difference theoretically predicted via GQE theory and calculated according to the standard Hamiltonian $\hat{H}$ shown in (18) is consistent with the phase difference obtained experimentally in the experiment in [65]. The potential energy inherent to the particles of the planet Earth of (18) can be equivalent to the classical gravitational potential energy of (16) with its main gravitational characteristics such as decay according to the inverse of the distance (height), attractiveness of the force and order of magnitude, for example, if it corresponds to potential energy like Weber's generalized one, as shown earlier via (10). The fact that nonlocal gravity within the framework of GQE theory seems to be consistent with gravitational induction of quantum interference, considering that the nonlocal potential $\hat{V}_M$ is canonical or fundamental such as the local potential, is very interesting and encourages further studies for a more detailed understanding.

## 6 Conclusions

In this work, we outlined a discussion of the state of the art of the research on some gravitational phenomena and theories of gravity. Specifically, we discuss how the GQE hypothesis can be associated with gravity, explain all aspects of such an interaction as its very weak magnitude, the nonlocal effects of gravity, the limit of the light velocity as consequence of the quantum vacuum, the validity of the nonlocal gravity and its description by means of GQE and many other interesting theoretical issues concerning the gravitational interaction.

We assert that some previous experiments indicated that GQE is consistent with some gravitational effects reported in the literature, as the weight reduction of capacitors, the gravitational shield generated by superconductors or the change in the value of the gravity acceleration of two magnets locked with each other in free fall.

It is worth to mention that in a next work we also intend to analyze a lot of relevant topics that deserve a more profound study, as the earlier mentioned complementarity (local and nonlocal) of the interactions and the association between inertia and gravity, Mach's principle and the principle of equivalence between gravitational mass and inertial mass. In addition, we also intend to explore other themes not discussed here as the dark matter or MOND, in order to investigate more profoundly the consistency of GQE for explaining all such phenomena.

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