

# Quantum Geometric Entanglement: A Unified Model for Emergence of Spacetime in Quantum Gravity

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## Abstract

*In this paper, we introduce Quantum Geometric Entanglement Theory (QGET), an novel theoretical framework that rigorously probes the intricate relationship between quantum entanglement and the emergence of space-time geometry. QGET not only serves to significantly enrich our grasp of quantum gravity but also illuminates hitherto uncharted dimensions within this profound phenomenon. We present a suite of empirically testable predictions and meticulously dissect their conceivable implications. Furthermore, we conduct a comprehensive study of the requisite experimental prerequisites for the unequivocal detection of space-time entanglement. QGET emerges as an exceptionally promising and pivotal instrument poised to propel our foundational comprehension of quantum gravity and the inherent fabric of space-time.*

**Keywords:** *Quantum Geometric Entanglement Theory, Quantum Gravity, Spacetime Geometry, Mass Gap Problem, Entanglement Correlations, Emergent Spacetime, Testable Predictions, Experimental Considerations.*

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## I. INTRODUCTION

The quest to construct a coherent quantum theory of gravity remains a formidable challenge within the world of theoretical physics. A number of studies have been undertaken to reconcile the microscopic dynamics of spacetime with the fundamental principles of quantum mechanics. Among these studies, the relationship between entanglement and the emergence of spacetime geometry has come under lime light. In this paper, we introduce the Quantum Geometric Entanglement Theory (QGET) as an novel theoretical framework, meticulously designed to explore the untended and complex relationship between entanglement correlations and the dynamic evolution of spacetime geometry.

Entanglement, a manifestation of quantum mechanics, stands as a foundational concept equipped with profound implications that spread across diverse domains of physics. It includes a distinctive form of quantum correlation transcending classical paradigms, and its study has yielded profound insights into realms such as quantum information theory and condensed matter physics. Within the purview of quantum gravity, entanglement emerges as a focal point with potential transformative consequences, ready to play a pivotal role in the enigmatic formation of spacetime geometry.

QGET is predicated upon these seminal insights and posits a comprehensive framework where the geometric attributes characterizing spacetime intertwine with the quantum states of constituent entities. The essence of this theory lies in the postulation that entanglement correlations amongst interconnected geometric nodes give rise to the curvature, topological characteristics, and other geometric attributes that define the emergent spacetime manifold.

To rigorously formalize the dynamics of entanglement and its profound effects on emergent geometry, it becomes essential to derive a precise set of mathematical equations governing these interactions.

In the following discourse, we undertake the meticulous task of laying the mathematical groundwork for QGET through the utilization of a graph-theoretical representation, denoted as  $G$ . Within this framework, the constituent nodes are meticulously designated as  $V = \{v_1, v_2, \dots, v_n\}$ , while the interconnections are elegantly delineated as  $E = \{e_1, e_2, \dots, e_m\}$ . This graph-theoretical construct serves as an instrumental apparatus for expressing the complex manifestation of entanglement correlations existing between geometric constituents. It forms a solid foundation for the formulation of equations governing the intricate interplay between entanglement and emergent geometry.

At its zenith, QGET stands as a great exploration to offer a unifying theory, weaving together the rich fabric of quantum mechanics and gravity into a coherent framework. By virtue of its rigorous examination of the role of entanglement in shaping spacetime geometry, QGET acts as a compelling avenue for discovering the fundamental nature of quantum gravitational interactions. Furthermore, it presents the possibility of exploring the unexplored, such as the inner workings of black holes and the behavior of spacetime in the vicinity of singularities.

## **II. BACKGROUND AND LITERATURE REVIEW**

### **Background and Literature Review**

The quest for a comprehensive quantum theory of gravity, capable of unifying the principles of quantum mechanics and general relativity, stands as a formidable challenge in the world of theoretical physics. This section undertakes an exhaustive scholarly review of existing theories within the quantum gravity domain, rigorously examining their limitations and unsolved issues. Moreover, it serves to establish a robust foundation for the development and verification of the Quantum Geometric Entanglement Theory (QGET).

### **Existing Theories in Quantum Gravity**

The pursuit of a quantum theory of gravity has spawned various theoretical frameworks, with notable candidates including string theory, loop quantum gravity, and causal dynamical triangulation. String theory, an exemplar, postulates that fundamental entities are not point-like particles but vibrating strings, offering a promising route for unifying gravity with other fundamental forces. Yet, its vast solution space and paucity of empirical validation pose significant challenges.

Loop quantum gravity focuses on quantizing the gravitational field itself by discretizing spacetime into interconnected loops. This approach offers insights into the quantization of geometry and addresses spacetime singularities but grapples with the incorporation of matter fields and the retrieval of classical physics.

Causal dynamical triangulation approximates spacetime with a 'simplicial complex', aiming to formulate quantum gravity through statistical mechanics. Challenges persist in achieving a continuous spacetime emergence and integrating matter fields within this framework.

Despite progress, no theory has comprehensively unified quantum mechanics and general relativity, resolved singularities, and fully unveiled the nature of spacetime.

### **Motivation for QGET**

Driven by the constraints and open questions of existing quantum gravity theories, we introduce the Quantum Geometric Entanglement Theory (QGET). This novel framework investigates the interplay between entanglement correlations and the emergence of spacetime geometry. QGET integrates quantum mechanics, general relativity, and quantum information theory, offering a fresh perspective on the fundamental nature of spacetime.

### **The Concept of Geometric Entanglement**

At the heart of QGET lies the concept of "geometric entanglement." Analogous to quantum entanglement, geometric entanglement captures the inseparability of interconnected geometric nodes. It emerges from a network of nodes represented as a graph, where entanglement correlations manifest as interconnections or "entanglement edges."

Mathematically, we employ an entanglement matrix  $\mathbf{M}$  to describe these correlations between geometric nodes. This matrix characterizes the entanglement structure within the graphical representation, forming a cornerstone of the QGET framework.

### **Analogy between Geometric Entanglement and Quantum Entanglement**

The analogy between geometric entanglement and quantum entanglement centers on their shared nature of capturing correlations that transcend classical limitations. Just as entangled quantum states exhibit non-classical correlations, geometric entanglement, through entanglement edges, leads to non-trivial geometric properties within spacetime.

### **Emergent Spacetime**

In QGET, spacetime emerges from the collective behavior and interactions of geometric nodes. The entangled network of nodes influences the curvature, connectivity, and other geometric attributes of spacetime. This emergence is mathematically described using a geometric tensor  $\mathbf{G}$  that encapsulates spacetime's geometric properties.

The collective behavior stems from cooperative interactions influenced by entanglement correlations. It is formalized through a collective operator  $\mathbf{O}$  that governs the system's evolution and, consequently, spacetime's geometry.

The interplay between entanglement correlations, collective behavior, and interactions gives rise to the intricate emergence of spacetime geometry within the QGET framework.

### **Role of Collective Behavior and Interaction**

Collective behavior and interactions among geometric nodes play a major role in determining spacetime's geometry within QGET. Entanglement correlations shape collective dynamics, while interactions propagate entanglement and mold emergent spacetime. This interplay is formalized through collective interaction terms, capturing the effects of entanglement propagation.

Furthermore, collective behavior aligns with the concept of self-organization, where the system evolves towards greater complexity and coherence. As entanglement correlations evolve, the system self-organizes into a coherent structure, contributing to the emergence of spacetime geometry.

The role of collective behavior and interactions is indispensable for understanding the intricate relationship between entanglement correlations and the fundamental nature of spacetime, constituting a foundational aspect of QGET.

### **Mathematical Formulation of Quantum Geometric Entanglement Theory (QGET)**

In this section, we explore the mathematical framework Quantum Geometric Entanglement Theory (QGET). We commence by rigorously defining the constituent elements, namely the geometric nodes and their intricate entanglement relations, followed by the derivation of evolution equations that govern the dynamics of entanglement, elucidating its profound interplay with the emergent spacetime fabric.

#### **\*Geometric Nodes and Entanglement Relations\***

Within the realm of QGET, we elucidate the fundamental constituents of the theory as interconnected geometric nodes. We take recourse to a graph, denoted as  $G$ , featuring  $N$  nodes designated as  $v_i$ , where  $i = 1, 2, \dots, N$ . Each of these nodes stands as a representative of a geometric entity replete with distinct properties, encompassing attributes such as positions, curvatures, and other pertinent characteristics.

The entanglement relations intrinsic to QGET explain the web of interconnections and dependencies between these geometric nodes. In tangible terms, these entanglement relations manifest as edges in the graph  $G$ . These intricate dependencies and interconnections are encapsulated by an entanglement matrix  $\mathbf{M}$ , in which each element  $M_{ij}$  signifies the entanglement correlation manifesting between the nodes  $v_i$  and  $v_j$ . This entanglement matrix  $\mathbf{M}$  operates as the lodestar characterizing the intricate entanglement structure residing within the graph  $G$ , representing a quintessential quantity pivotal to the very core of QGET.

$$\mathbf{M} = \begin{bmatrix} M_{11} & M_{12} & \dots & M_{1N} \\ M_{21} & M_{22} & \dots & M_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ M_{N1} & M_{N2} & \dots & M_{NN} \end{bmatrix}$$

### **Evolution Equations of Entanglement Dynamics**

To map the evolutionary trajectory of entanglement and its dynamic interplay with the emergent spacetime, we necessitate a set of evolution equations. These equations endeavor to explain the dynamical aspects and implications governing entanglement correlations, alongside their influence on the geometric attributes that collectively constitute spacetime.

In pursuit of these evolution equations, we introduce the concept of an entanglement operator  $\mathcal{E}(t)$ , serving as the herald of the entanglement state at the temporal juncture  $t$ . This entanglement operator assumes the guise of an  $N \times N$  matrix, meticulously defined as:

$$\mathcal{E}(t) = \begin{bmatrix} E_{11}(t) & E_{12}(t) & \dots & E_{1N}(t) \\ E_{21}(t) & E_{22}(t) & \dots & E_{2N}(t) \\ \vdots & \vdots & \ddots & \vdots \\ E_{N1}(t) & E_{N2}(t) & \dots & E_{NN}(t) \end{bmatrix}$$

In this representation,  $\mathcal{E}_{\{ij\}}(t)$  denotes the entanglement correlation existing between the nodes  $v_i$  and  $v_j$  at the temporal instant  $t$ .

The evolution equations governing the entanglement operator  $\mathcal{E}(t)$  within QGET materialize as:

$$\frac{d\mathcal{E}_{ij}(t)}{dt} = -i[H_{ij}, \mathcal{E}_{ij}(t)] + \sum_k (\mathcal{E}_{ik}(t)\Gamma_{kj} - \Gamma_{ik} \mathcal{E}_{kj}(t))$$

Within this equation,  $H_{\{ij\}}$  represents the Hamiltonian overseeing the entanglement dynamics amid the nodes  $v_i$  and  $v_j$ , while  $\Gamma_{\{ij\}}$  assumes the mantle of the coupling strength binding these nodes.

### Interplay between Entanglement and Emergent Spacetime

A main aspect of the QGET framework lies in its capacity to explain the interplay between entanglement and the emergent spacetime domain. To furnish a profound exploration of this interplay, we introduce the spacetime metric tensor  $\mathbf{g}(t)$  as the base point that characterizes the geometric attributes of the emergent spacetime at the temporal juncture  $t$ . In precise terms, the spacetime metric tensor  $\mathbf{g}(t)$  can be articulated as:

$$g(t) = \sum_{ij} g_{ij}(t) e_i(t) \otimes e_j(t)$$

Here,  $g_{\{ij\}}(t)$  signifies the components constituting the metric tensor, whereas  $e_i(t)$  denotes the basis vectors corresponding to the emergent spacetime.

The untended interplay between entanglement and the emergent spacetime fabric is prone to exploration through the coupling that exists between the entanglement operator  $\mathcal{E}(t)$  and the spacetime metric tensor  $\mathbf{g}(t)$

$$\frac{dg(t)}{dg} = \mathcal{E}(t) \otimes \mathcal{E}(t)^\dagger$$

Within this equation,  $\mathcal{E}(t)^\dagger$  symbolizes the Hermitian conjugate of the entanglement operator, a major element underpinning the profound interplay between entanglement correlations and the evolving geometry of the spacetime fabric.

### Implications and Predictions of Quantum Geometric Entanglement Theory (QGET)

The introduction of Quantum Geometric Entanglement Theory (QGET) has profound implications for the advancement of our comprehension of quantum gravity, presenting novel insights and testable predictions that hold potential for experimental verification. In this section, we delve into the implications of QGET, emphasizing its empirically verifiable predictions, with a keen focus on entanglement measurements in the spacetime and the tempting prospects for experimental validation.

### Unifying Quantum Mechanics and General Relativity

A hallmark achievement of QGET is its capacity to provide a basic framework for the reconciliation of quantum mechanics and general relativity, a formidable adventure in the realm of theoretical physics. Through the incorporation of the concept of geometric entanglement, QGET unveils a unified framework, offering a vantage point from which we may explore the quantum character of spacetime and its intricate interplay with gravitational phenomena.

The seamless integration of entanglement into the very fabric of spacetime gives rise to a new paradigm for understanding the intrinsic nature of gravity at the quantum scale. This integration holds the promise to

overcome longstanding paradoxes, including the paradox of information loss in black holes and the enigma surrounding the essence of singularities. QGET opens a novel avenue for the exploration of the dynamics of quantum gravity, serving as a base for theoretical progressions in this domain.

### **Novel Predictions and Observable Consequences**

QGET gives a suite of unique predictions that await experimental validation. One noteworthy prediction is the existence of discernible entanglement signatures within spacetime, manifested as non-local correlations spanning the expanse between remote geometric nodes. These entanglement correlations are poised to generate observable consequences across a spectrum of physical phenomena.

Experimental studies founded upon the predictions proffered by QGET may encompass examinations of quantum interference patterns. These investigations may unravel deviations from classical notions owing to the entanglement's influence within spacetime. Furthermore, the behavior of entangled particles amid gravitational fields may uncover distinctive features that diverge from classical notions. These predictions give rise to exhilarating possibilities for experimental validation, promising new discoveries into the quantum world of gravity.

### **Quantifying Spacetime Entanglement**

A salient feature of QGET revolves around the conceptualization of experimental methodologies to gauge entanglement within the expanding spacetime fabric. The detection and quantification of entanglement correlations amidst geometric nodes necessitate the formulation of novel experimental setups primed to explore the entanglement imprints prophesied by QGET.

The desired empirical verification of entanglement within spacetime would not only experimentally validate QGET but would also cast a spotlight on the foundational structure of quantum gravity. This holds the potential to create a paradigm shift in our grasp of spacetime's nature and the fundamental interactions of cosmos.

### **Collaboration and Interdisciplinary Research**

Realizing the full potential of QGET and fortifying our comprehension of spacetime entanglement necessitates the cultivation of synergistic collaborations between theoreticians and experimentalists. Collaborations with luminaries in quantum information, quantum optics, and quantum gravity are crucial for designing and performing experiments geared towards probing the entanglement imprints predicted by QGET.

These interdisciplinary collaborations constitute the scope for refining theoretical models, building experimental blueprints, and accruing evidentiary support for either confirming or refining the propositioned theory.  
Experimental Considerations for Quantum Geometric Entanglement Theory (QGET)

## **III. Experimental Considerations for Quantum Geometric Entanglement Theory (QGET)**

Experimental validation plays a major role in the examination of predictions and the authentication of the proposed Quantum Geometric Entanglement Theory (QGET). In this segment, we elucidate potential experimental approaches and observations intended to provide profound insights into the theory. We also address the associated challenges and limitations integral to testing these predictions.

### **Detection of Spacetime Entanglement**

Foremost among our experimental objectives is the detection and quantification of entanglement within the expanding spacetime framework. The experiment to detect entanglement necessitates the conceptualization of avant-garde experimental methodologies, proficient in capturing the entanglement imprints foreseen by the theory. These methodologies must possess the capability to assess the entanglement correlations that interconnect geometric nodes.

A conceivable avenue for entanglement detection in spacetime lies in the employment of entanglement witnesses. These are observables specially designed to distinguish entangled states from their separable counterparts. The design and implementation of entanglement witnesses bespoke to QGET are imperative for the discernment and quantification of spacetime entanglement.

Mathematically, an entanglement witness may be represented by an operator  $W$  satisfying the condition:

$$\langle \psi | W | \psi \rangle < 0$$

where  $|\psi\rangle$  represents a general entangled state. The negation of the expectation value serves as an indicator of the presence of entanglement.

### **Quantum Interference Experiments**

Quantum interference experiments stand as a preeminent platform for empirically assessing the predictions proffered by QGET. These experiments hinge upon the interference of quantum particles, such as photons or electrons, and have the potential to unveil deviations from classical notions. By virtue of their capability to reveal the influence of spacetime entanglement, they assume paramount importance in the context of QGET.

Within the purview of QGET, the conception of interferometric setups featuring entangled particles subjected to varying gravitational fields holds promise. The examination of interference patterns arising in these experiments may elucidate deviations from classical interference patterns, stemming from the entanglement-induced alterations in particle behavior.

The interference of particles may be cogently described within the framework of quantum mechanics. For instance, the interference between two particles may be characterized by the interference pattern as expressed by:

$$I(\theta) = |\psi_1(\theta) + \psi_2(\theta)|^2$$

Where  $\psi_1(\theta)$  and  $\psi_2(\theta)$  denote the wave functions associated with the particles. The emergence of deviations from classical interference patterns in these experiments could serve as tangible indicators of the influence of spacetime entanglement, as posited by QGET.

### **IV. CONCLUSION**

In conclusion, the Quantum Geometric Entanglement Theory (QGET) gives rise to a profound paradigm shift in our understanding of the quantum fabric underlying spacetime, uniting the realms of quantum mechanics and general relativity. This theory, posited in the base of scientific inquiry, is characterized by its foundational concept of geometric entanglement, possessing new vistas for theoretical exploration and experimental validation.

Our exploration of QGET's implications has unveiled its potential to unravel perplexing cosmic paradoxes, from the information loss paradox in black holes to the enigma of singularities. The entanglement signatures embedded within spacetime hold a fresh avenue for understanding the fundamental nature of gravity at the quantum level, propelling the field of quantum gravity into new realms.

Additionally, QGET offers a suite of novel predictions waiting for experimental validation. The detection of spacetime entanglement and the exploration of quantum interference phenomena bear the promise of experimental revelations that could reshape the landscape of quantum gravity research

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