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Article

Quantum Entanglement Asymmetry and the Cosmic Matter-Antimatter Imbalance: A Theoretical and Observational Analysis

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Abstract: In this study, we investigate Quantum Entanglement Asymmetry (QEA) as a potential explanation for the matter-antimatter imbalance observed in the universe. By integrating quantum mechanics with cosmological phenomena, the study proposes a model in which quantum entanglement among particle-antiparticle pairs in the early universe leads to an asymmetry favoring matter. Through theoretical development and numerical simulations, we explore how this model predicts unique patterns in Cosmic Microwave Background (CMB) anisotropies and the distribution of matter, setting a foundation for empirical verification. The study aims to enhance the understanding of cosmological asymmetries and highlight the significance of quantum entanglement in the universe's evolution.

Keywords: quantum entanglement asymmetry; matter-antimatter imbalance; cosmic microwave background anisotropies; friedmann equations; cosmological evolution

1. Introduction

The observable universe exhibits a pronounced asymmetry between matter and antimatter, a fundamental cosmological phenomenon that profoundly affects our understanding of the universe's origin, structure, and ultimate fate. This asymmetry is evidenced by the overwhelming predominance of matter over antimatter in the universe. This condition is essential for galaxies, stars, planets, and life as we know it. Theoretical frameworks and experimental observations within the Standard Model of particle physics and cosmology suggest that the Big Bang should have produced matter and antimatter in equal quantities. However, this parity is not observed in the current cosmological epoch, leading to one of the most significant puzzles in modern physics [1,2]. The significance of this matter-antimatter asymmetry extends beyond theoretical interest; it underpins the very structure and evolution of the universe. Without this fundamental asymmetry, matter and antimatter would have annihilated each other in the early universe, leaving behind a cosmos filled with nothing but radiation. The persistence of matter, therefore, necessitates mechanisms that favor its survival over antimatter, a challenge that has spurred extensive theoretical and experimental research in particle physics and cosmology [2,3].

Current explanations within the Standard Model, including the combined charge-parity (CP) violation, provide mechanisms through which matter-antimatter asymmetry could theoretically emerge. CP violation, the phenomenon where the laws of physics change when particles are replaced by their antiparticles and their spatial coordinates are inverted, has been observed experimentally but does not account for the observed magnitude of asymmetry. This inadequacy suggests the existence of processes beyond the Standard Model, necessitating theoretical frameworks to adequately explain the observed imbalance [4,5].

Several theoretical frameworks have been developed to explore the asymmetry between matter and antimatter. These theories incorporate complex physical and mathematical principles, aiming to account for the observed imbalance through mechanisms that extend beyond the Standard Model of particle physics.

1.1. CP Violation and the Standard Model

CP violation is a cornerstone of theoretical attempts to explain the baryon asymmetry of the universe (BAU). In the Standard Model, CP violation is quantified by the complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which describes the mixing of quark flavors by weak interactions. The CP-violating phase, δ_{CP} , enters in the combination of CKM matrix elements, such as in the Jarlskog invariant J_{CP} , which is a measure of the amount of CP violation and is given by

$$J_{CP} = \text{Im} \left(V_{ij} V_{kl} V_{il}^* V_{kj}^* \right), \quad (1)$$

where V_{ij} are the elements of the CKM matrix, however, the magnitude of CP violation observed in the Standard Model is orders of magnitude too small to account for the BAU [6].

1.2. Electroweak Baryogenesis

Electroweak baryogenesis relies on a first-order phase transition in the early universe, which would provide the out-of-equilibrium conditions necessary for baryogenesis as per Sakharov's criteria. The strength of the phase transition is parameterized by the ratio of the Higgs field's vacuum expectation value to the critical temperature, $\phi(T_c)/T_c$. A strong first-order phase transition, necessary for electroweak baryogenesis, requires $\phi(T_c)/T_c > 1$. However, lattice simulations suggest that for a Higgs mass above approximately 70 GeV, the electroweak phase transition is not strongly first-order [7], making this mechanism incompatible with current particle physics observations.

1.3. Leptogenesis

Leptogenesis introduces the possibility of generating the BAU through an initial excess of leptons. The key equation in leptogenesis relates the lepton asymmetry, ϵ_L , to CP-violating decays of heavy right-handed neutrinos, N , into leptons, l , and Higgs bosons, ϕ , as follows:

$$\epsilon_L = \frac{\Gamma(N \rightarrow l\phi) - \Gamma(N \rightarrow \bar{l}\bar{\phi})}{\Gamma(N \rightarrow l\phi) + \Gamma(N \rightarrow \bar{l}\bar{\phi})}, \quad (2)$$

where Γ denotes the decay rate. Sphaleron processes facilitate the conversion of lepton asymmetry to baryon asymmetry. Despite its theoretical appeal, the model's reliance on the existence and properties of heavy right-handed neutrinos places it beyond the current empirical reach [8].

1.4. Affleck-Dine Mechanism

The Affleck-Dine mechanism leverages the dynamics of scalar fields carrying baryon number, ϕ_B , evolving in the early universe. The baryon asymmetry is generated through the evolution of ϕ_B in a potential $V(\phi_B)$, which can be represented as

$$\dot{\rho}_B + 3H\rho_B = -\Gamma_\phi \rho_B + \text{Im} \left(\frac{\partial V}{\partial \phi_B} \dot{\phi}_B^* \right), \quad (3)$$

where ρ_B is the baryon number density, H is the Hubble parameter, Γ_ϕ is the decay rate of ϕ_B , and $\dot{\phi}_B$ is the time derivative of ϕ_B . This mechanism requires conditions for baryogenesis realized in supersymmetric extensions of the Standard Model, making its predictions contingent on the discovery of supersymmetry [9].

1.5. Limitations of Existing Theories

While these theories provide frameworks for understanding the BAU, they also highlight the challenges in constructing a comprehensive theory within the constraints of current experimental evidence. The insufficiency of CP violation in the Standard Model, the conditions for electroweak baryogenesis not met by the observed Higgs mass, the speculative nature of leptogenesis, and the

dependency of the Affleck-Dine mechanism on unconfirmed supersymmetry, collectively underscore the need for innovative approaches to explain the matter-antimatter asymmetry.

1.6. Objective

The quest to understand the observed asymmetry between matter and antimatter in the universe has led to the exploration of various theoretical frameworks, each with its own merits and limitations. This paper introduces the Quantum Entanglement Asymmetry (QEA) hypothesis as a paradigm designed to address the shortcomings of current models and provide a comprehensive explanation for the matter-antimatter imbalance. The QEA hypothesis posits that quantum entanglement, a fundamental principle of quantum mechanics, played a crucial role in the early universe, leading to an asymmetrical production of matter over antimatter through a previously unexplored mechanism.

1.6.1. Foundational Principles of the QEA Hypothesis

The QEA hypothesis is grounded in the principle that during the Planck epoch, the universe was a quantum system characterized by extensive entanglement among its constituent particles. Unlike conventional models focusing on CP violation and baryogenesis, the QEA approach suggests that asymmetries in quantum entanglement patterns could have biased the universe towards a matter-dominated state. Specifically, it proposes that:

1. In the early universe, particle-antiparticle pairs were produced in a state of quantum entanglement.
2. Asymmetries in entanglement configurations led to a preferential selection of matter over antimatter, even in the absence of significant CP violation.
3. This mechanism was amplified during cosmic inflation, resulting in the large-scale matter dominance observed today.

1.6.2. Addressing the Limitations of Existing Theories

The QEA hypothesis offers solutions to several key limitations of existing theories:

- Unlike models requiring large CP violation, the QEA hypothesis does not rely on mechanisms that are not observed or are insufficient within the Standard Model.
- It provides a novel mechanism for matter-antimatter asymmetry that does not necessitate a first-order electroweak phase transition, circumventing the challenges posed by the observed Higgs mass.
- By invoking quantum entanglement, the QEA hypothesis introduces a mechanism for asymmetry that is independent of the specifics of particle physics models, such as the existence of heavy right-handed neutrinos or supersymmetric particles.

The introduction of the QEA hypothesis represents a significant shift in the approach to understanding the matter-antimatter asymmetry, offering a pathway to reconcile existing empirical observations with a fundamental principle of quantum mechanics. This paper aims to elaborate on the theoretical underpinnings of the QEA hypothesis, explore its implications for cosmology and particle physics, and propose experimental and observational strategies to test its validity.

1.7. Contribution

This paper aims to make several significant contributions to cosmology and particle physics by introducing and exploring the QEA hypothesis. By proposing a fresh mechanism for the matter-antimatter asymmetry observed in the universe, this work extends beyond existing theoretical frameworks, offering new insights and potential solutions to one of the most profound mysteries in modern physics.

1.7.1. Theoretical Framework

The primary contribution of this paper is the establishment of the QEA hypothesis as a theoretical framework for understanding matter-antimatter asymmetry. This hypothesis integrates principles of quantum mechanics, particularly quantum entanglement, with cosmological models of the early universe, thereby:

- Introducing the concept of entanglement asymmetry as a fundamental process that could lead to the observed predominance of matter.
- Proposing a mechanism that operates independently of the large CP violation or specific beyond-the-Standard-Model physics, which are common requisites in existing theories.

1.7.2. Implications for Cosmology and Particle Physics

The QEA hypothesis has profound implications for both cosmology and particle physics, potentially reshaping our understanding of the early universe's evolution and the fundamental interactions that governed it:

- It suggests that quantum entanglement can have macroscopic, observable effects on the universe's large-scale structure, linking quantum mechanics with cosmological phenomena.
- The hypothesis could lead to new predictions regarding the distribution of matter and antimatter in the universe, offering insights that could be tested with future astronomical observations and particle physics experiments.

1.7.3. Potential for Empirical Validation

Another significant contribution of this work is the identification of potential avenues for empirically validating the QEA hypothesis. By proposing specific predictions and effects that could be observed, the paper sets the stage for future experimental and observational studies, such as:

- Anomalies in the cosmic microwave background radiation that could indicate the influence of quantum entanglement in the early universe.
- Patterns in the distribution of dark matter and baryonic matter reflect the entanglement asymmetry mechanism.

1.7.4. Broadening the Dialogue

Finally, this paper contributes to broadening the interdisciplinary dialogue between these fields by proposing a hypothesis that bridges quantum mechanics and cosmology. It invites physicists from diverse backgrounds to explore the implications of quantum entanglement in a cosmological context, potentially opening up new research directions and collaborations.

The Quantum Entanglement Asymmetry hypothesis enriches the scientific discourse on matter-antimatter asymmetry by providing a fresh perspective grounded in fundamental physics. Its exploration contributes to the ongoing quest to understand the universe's origins, evolution, and laws governing it, marking a step forward in synthesizing quantum mechanics and cosmology.

2. Theoretical Framework

Here, we delineate the conceptual underpinnings and mathematical formulations that constitute the backbone of our QEA model, which is foundational for its application to cosmological phenomena.

2.1. Quantum Entanglement in Cosmology

Quantum entanglement represents a cornerstone in the foundation of quantum mechanics, positing that pairs or groups of particles can become interconnected such that the state of one instantaneously influences the state of another, irrespective of the distance separating them. This

non-local phenomenon challenges classical notions of causality and has significant implications for the early universe's conditions.

2.1.1. Principles of Quantum Entanglement

Entanglement is characterized by the peculiar property that the quantum state of each particle within an entangled pair or group cannot be described independently of the state of the others. This is represented mathematically by a wave function encompassing the entire system in a superposition state. For instance, an entangled state of two particles can be expressed as:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle_A|1\rangle_B + |1\rangle_A|0\rangle_B), \quad (4)$$

where $|0\rangle$ and $|1\rangle$ denote orthogonal quantum states of particles A and B . Equation (4) illustrates the entanglement of particles A and B in a superposition of being in two states simultaneously, highlighting the non-local correlations that define entanglement [10].

2.1.2. Relevance to Early Universe Conditions

In the context of the early universe, particularly during the Planck epoch, the dense and hot conditions prevalent could have facilitated the creation of entangled particle pairs. These early instances of entanglement are hypothesized to influence the universe's subsequent thermal history, including the asymmetry between matter and antimatter. The cosmic inflation theory posits that the rapid expansion of space during the early moments of the universe could stretch quantum fluctuations, including entangled states, across macroscopic distances. This inflationary period is critical for understanding how quantum mechanical phenomena at microscopic scales could influence the universe's large-scale structure, suggesting a framework where quantum entanglement plays a pivotal role in the evolution of the cosmos [11].

The exploration of quantum entanglement within cosmological models provides a unique lens through which the asymmetry between matter and antimatter can be re-evaluated. By proposing that entangled states in the early universe could lead to preferential outcomes favoring matter over antimatter, we introduce a mechanism that could explain the observed imbalance without relying solely on CP violation or other mechanisms beyond the Standard Model.

2.1.3. Entanglement and Cosmic Inflation

The theory of cosmic inflation offers a compelling narrative for the rapid expansion of space shortly after the Big Bang. This dramatic growth could magnify quantum entanglements across the universe, embedding these quantum correlations within the fabric of cosmic microwave background radiation and influencing the distribution of galaxies and dark matter. Such a perspective aligns with observations of the CMB and the universe's large-scale structure, providing a quantum mechanical framework for cosmological evolution [12,13].

2.1.4. Comprehensive Derivation of F within the QEA Framework

The QEA framework introduces a sophisticated approach to explaining the observed matter-antimatter asymmetry in the universe, grounded in the principles of quantum entanglement, CP-violation, and their integration within cosmological models. This subsection details the theoretical journey from identifying relevant quantum fields, through the development of their theoretical models, to the conceptual derivation of $F(r, p)$, the function signifying the energy contributions from entangled states under the influence of CP-violating interactions in curved spacetime.

Quantum Fields in QEA

To anchor the QEA framework, we identified critical quantum fields, including scalar fields like the Higgs, fermion fields encompassing quarks and leptons, gauge fields responsible for mediating fundamental forces, and potential contributions from hypothetical fields such as axions. These fields form the bedrock for exploring entanglement and CP-violation phenomena in the early universe.

Theoretical Models and Lagrangian Formulation

For each quantum field, we developed Lagrangian densities capturing the essence of field dynamics, interactions, and the peculiarities introduced by CP-violation and spacetime curvature. Notably:

- Scalar Field Lagrangian: $\mathcal{L}_{\text{scalar}} = \sqrt{-g} \left(\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) + \xi R \phi^2 \right)$, addressing mass generation and scalar field coupling to gravity.
- Fermion Field Lagrangian: $\mathcal{L}_{\text{fermion}} = \sqrt{-g} (\bar{\psi} (i\gamma^\mu D_\mu - m) \psi)$, integrating fermions' mass acquisition and their gauge interactions.
- Gauge Field Lagrangian: $\mathcal{L}_{\text{gauge}} = -\frac{1}{4} \sqrt{-g} F_{\mu\nu} F^{\mu\nu}$, illustrating the propagation and interaction of force carriers.

Conceptual Derivation of $F(r, p)$

The function $F(r, p)$ encapsulates the energy contributions from entangled quantum states, factoring in CP-violation and the effects of curved spacetime. The derivation process involved a conceptual formulation that integrates these phenomena:

$$F(r, p) = \int d^4x \sqrt{-g} (\mathcal{L}_{\text{field}} + \mathcal{L}_{\text{CP-violation}} + \mathcal{L}_{\text{curvature}}) \quad (5)$$

This expression for F represents an integral over spacetime, combining the contributions from field dynamics ($\mathcal{L}_{\text{field}}$), CP-violating interactions ($\mathcal{L}_{\text{CP-violation}}$), and the influence of spacetime curvature ($\mathcal{L}_{\text{curvature}}$). While a numerical computation of F was beyond our scope, this formulation provides a theoretical foundation for integrating QEA into cosmological models and making observable predictions.

2.1.5. Conceptual Derivation of G within the QEA Framework

Parallel to the derivation of F , the QEA framework necessitates a comprehensive understanding of $G(r, p)$, a function representing the contributions from entangled states to the pressure in the universe under the influence of CP-violating interactions and curved spacetime dynamics. This subsection outlines the theoretical development leading to the conceptual formulation of G .

Pressure Contributions from Quantum Fields

Identifying quantum fields relevant to the QEA hypothesis also underpins the development of G . Scalar fields, fermion fields, gauge fields, and hypothetical fields, such as axions, all contribute to the universe's pressure in addition to its energy density. The formulation of G involves:

- Analyzing the contributions of these fields to the pressure in curved spacetime, considering both their kinetic and interaction terms.
- Incorporating the effects of quantum entanglement and CP-violation, which may modify the standard pressure contributions from these fields.

Theoretical Models and Lagrangian Formulation

The Lagrangian densities for the quantum fields, previously outlined, serve as the foundation for deriving G , with additional considerations for pressure:

$$G(r, p) = \int d^4x \sqrt{-g} (\mathcal{P}_{\text{field}} + \mathcal{P}_{\text{CP-violation}} + \mathcal{P}_{\text{curvature}}) \quad (6)$$

This expression for G integrates over spacetime, combining the pressure contributions from field dynamics ($\mathcal{P}_{\text{field}}$), CP-violating interactions ($\mathcal{P}_{\text{CP-violation}}$), and the influence of spacetime curvature ($\mathcal{P}_{\text{curvature}}$). Similar to F , this formulation underscores the theoretical approach to quantifying how entangled states and CP-violation impact the universe's pressure.

Implications for Cosmology and QEA

The development of G complements the theoretical narrative of QEA by highlighting the role of quantum entanglement and CP-violation in influencing the universe's energy density and pressure. This dual contribution is essential for a holistic understanding of the universe's evolution, particularly in the early universe, where quantum effects and spacetime curvature significantly interplay.

2.2. Integration of Quantum Entanglement Asymmetry into the Cosmological Model

Following the detailed exploration of QEA and its foundational principles in sections 2.1.1 through 2.1.3, this section explains the practical integration of the derived functions F and G into the cosmological model. We aim to elucidate how these functions, representative of energy contributions and pressure effects from quantum entanglement, can significantly modify the dynamics of the universe's expansion and its overall evolution.

2.2.1. Modifications to the Friedmann Equations

Incorporating the functions F and G into the Friedmann equations necessitates a reevaluation of the universe's expansion dynamics, accounting for the energy contributions and pressure effects from quantum entanglement and CP-violating interactions. The standard Friedmann equations, within the context of a flat universe, are given by:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} \quad (7)$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3} \quad (8)$$

where H is the Hubble parameter, a is the scale factor, ρ is the energy density, p is the pressure, G is the gravitational constant, and Λ is the cosmological constant.

To integrate F and G , we consider them as modifications to ρ and p respectively, reflecting the additional contributions from quantum entanglement:

$$\rho_{\text{total}} = \rho + \rho_{\text{QEA}} = \rho + F(a, \dot{a}, \ddot{a}, \dots) \quad (9)$$

$$p_{\text{total}} = p + p_{\text{QEA}} = p + G(a, \dot{a}, \ddot{a}, \dots) \quad (10)$$

These modifications lead to revised Friedmann equations that capture the nuanced effects of QEA on the cosmological scale. The task then becomes solving these equations to explore the implications for cosmic expansion and acceleration, potentially offering new insights into the early universe's dynamics and the nature of dark energy.

This development underscores the QEA framework's potential to enrich our understanding of cosmology, integrating quantum mechanical phenomena with classical gravitational theory.

2.2.2. Implications for Cosmic Evolution

The integration of F and G into the cosmological model unveils new dimensions in our comprehension of cosmic evolution. By accounting for the energy contributions and pressure effects from quantum entanglement, encapsulated by F and G , we are provided with a richer framework to investigate several cosmic phenomena:

- **Matter-Antimatter Asymmetry:** The modifications introduced by F and G offer a distinct perspective on the imbalance between matter and antimatter, suggesting that quantum entanglement and CP-violating interactions could play a significant role in this fundamental asymmetry.
- **Cosmic Structure Formation:** The influence of F and G extends to the formation and distribution of cosmic structures. Their effects on the dynamics of cosmic expansion may lead to observable deviations in the universe's large-scale structure.
- **Dark Energy and Cosmic Acceleration:** The revised Friedmann equations, incorporating F and G , might provide insights into the nature of dark energy and the mechanism behind the accelerated expansion of the universe.

The next frontier is empirical validation of these theoretical predictions through observations of the CMB, galaxy distribution, and other cosmological phenomena. Such validation could confirm the significance of quantum entanglement asymmetry in shaping the universe's evolution, marking a pivotal advancement in cosmology.

2.3. QEA Hypothesis

The QEA hypothesis posits that the asymmetry between matter and antimatter observed in the universe arises from an intrinsic asymmetry in quantum entanglement processes occurring during the early universe. This section outlines the hypothesis's core concepts, the proposed mechanism of entanglement asymmetry, and its theoretical underpinnings.

2.3.1. Mechanism of Entanglement Asymmetry

The QEA hypothesis suggests that during the Planck epoch, when the universe was dense and hot, quantum fluctuations led to the creation of particle-antiparticle pairs in entangled states. Unlike conventional scenarios where such pairs would annihilate symmetrically, the QEA mechanism proposes that:

$$|\Psi_{\text{QEA}}\rangle = \alpha|0\rangle_A|1\rangle_B + \beta|1\rangle_A|0\rangle_B, \quad (11)$$

where $|\alpha|^2 \neq |\beta|^2$. This inequality between the coefficients reflects an asymmetry in the entanglement probabilities, favoring the survival of matter over antimatter. Here, $|\alpha|^2$ and $|\beta|^2$ represent the probabilities of finding the system in either state, with their difference directly contributing to the net matter over antimatter in the universe.

2.3.2. Theoretical Basis

The theoretical basis of the QEA hypothesis draws from the principles of quantum field theory and cosmology, incorporating aspects of the inflationary model and quantum mechanics. The hypothesis extends the standard model of cosmology by incorporating a distinct interaction in the quantum field theory that describes the early universe. This interaction is characterized by violating the CP symmetry specific to the entangled states, leading to the preferential production of matter over antimatter. The mathematical formulation of the QEA hypothesis involves modifications to the Hamiltonian that governs particle interactions, introducing terms that break the symmetry between matter and antimatter production in entangled states. These terms can be represented as:

$$\hat{H}_{\text{QEA}} = \hat{H}_{\text{SM}} + \Delta\hat{H}, \quad (12)$$

where \hat{H}_{SM} is the Standard Model Hamiltonian, and $\Delta\hat{H}$ represents the additional terms responsible for entanglement asymmetry. The specific form of $\Delta\hat{H}$ is derived from theoretical considerations of quantum gravity and high-energy physics, which remain speculative but offer a plausible framework for the observed asymmetry (see 4.1.1).

2.3.3. Implications and Predictions

The QEA hypothesis offers several testable predictions, such as specific signatures in the CMB radiation and patterns in the distribution of cosmic structures that could result from the early universe's entanglement asymmetry. Additionally, it suggests that similar asymmetries might be observable in high-energy particle interactions, providing a potential avenue for experimental verification.

The introduction of the QEA hypothesis represents a significant shift in our approach to understanding the universe's fundamental asymmetry. By invoking principles of quantum entanglement, the hypothesis offers a perspective that bridges gaps in our current understanding, potentially unlocking new physics governing the universe's earliest moments and its large-scale structure.

2.4. Sakharov Conditions

The landmark criteria proposed by Andrei Sakharov in 1967 [4] outline the necessary conditions for generating the BAU. The QEA hypothesis adheres to these conditions through a unique mechanism rooted in quantum entanglement and its inherent asymmetries. This section elucidates how the QEA hypothesis satisfies each of Sakharov's conditions in its context.

2.4.1. Baryon Number Violation

The first of Sakharov's conditions — baryon number violation — is crucial for allowing processes that differentiate between matter and antimatter. Within the framework of the QEA hypothesis, this violation is not mediated by conventional particle interactions but emerges from the asymmetric entanglement states that preferentially produce baryons over antibaryons. The asymmetry in the entangled states, as described by Equation (11), inherently leads to processes where the conservation of baryon number is not upheld, thus satisfying this condition in a fundamentally new way.

2.4.2. C and CP Symmetry Violation

The second condition posited by Sakharov is the violation of charge conjugation (C) symmetry and the combined charge-parity (CP) symmetry. The QEA hypothesis proposes that the asymmetry in quantum entanglement intrinsically violates CP symmetry, as the process preferentially favors the creation of matter over antimatter. This violation is embedded in the quantum mechanics of the entangled states and does not rely on the CP-violating interactions traditionally considered in particle physics. Therefore, the QEA mechanism introduces a form of CP violation that is fundamentally tied to the properties of quantum entanglement and its role in the early universe.

2.4.3. Departure from Thermal Equilibrium

The third condition requires a departure from thermal equilibrium, essential for preventing the annihilation of any generated asymmetry. In the context of the QEA hypothesis, the universe's rapid expansion during the inflationary period provides a non-equilibrium backdrop that amplifies the effects of entanglement asymmetry. The inflation-driven expansion separates entangled pairs, preventing their mutual annihilation and allowing the asymmetry to be frozen into the fabric of the universe. This mechanism presents a unique route to satisfying Sakharov's third condition, leveraging the dynamics of cosmic inflation to preserve the generated baryon asymmetry.

2.4.4. Integration within the QEA Framework

By satisfying Sakharov's conditions through mechanisms rooted in quantum entanglement and cosmological principles, the QEA hypothesis offers a compelling and innovative explanation for the matter-antimatter asymmetry observed in the universe. This approach not only adheres to the foundational requirements identified by Sakharov but also extends them into quantum physics, suggesting that the origins of cosmic asymmetry may lie in the intrinsic properties of quantum mechanics as manifested in the early universe.

2.5. Integration of Quantum Entanglement Asymmetry into the Cosmological Model

The QEA hypothesis introduces a perspective on the universe's asymmetry between matter and antimatter. It suggests that quantum entanglement among early universe particles was crucial in biasing the universe towards a matter-dominated state. This section provides a rigorous mathematical framework for incorporating the QEA hypothesis into the cosmological model. It aims to explain the observed matter-antimatter asymmetry and its implications for the universe's evolution.

2.5.1. Theoretical Underpinnings of QEA

During the Planck epoch, characterized by extreme densities and energies, quantum entanglement potentially led to the asymmetric creation of particle-antiparticle pairs. This entanglement-induced asymmetry is mathematically represented as:

$$\Psi_{\text{ent}} = \alpha|\text{particle}\rangle|\text{antiparticle}\rangle + \beta|\text{antiparticle}\rangle|\text{particle}\rangle, \quad (13)$$

where α and β are complex coefficients whose magnitudes square represent the probabilities of the entangled states, and $|\alpha|^2 \neq |\beta|^2$ signifies the asymmetry favoring matter over antimatter.

2.5.2. Mathematical Formulation

To quantify the impact of QEA on cosmological parameters, we introduce modifications to the energy density ρ_{QEA} and pressure p_{QEA} in the early universe:

$$\rho_{\text{QEA}} = \int \Psi_{\text{ent}}^\dagger \hat{H}_{\text{QEA}} \Psi_{\text{ent}} d^3x, \quad (14)$$

$$p_{\text{QEA}} = -\frac{1}{3} \int \Psi_{\text{ent}}^\dagger \vec{\nabla} \cdot \hat{\vec{P}}_{\text{QEA}} \Psi_{\text{ent}} d^3x, \quad (15)$$

where \hat{H}_{QEA} and $\hat{\vec{P}}_{\text{QEA}}$ denote the Hamiltonian and momentum operators accounting for QEA effects, respectively.

2.5.3. Implications for Cosmological Evolution

Integrating QEA into the cosmological model affects the Friedmann equations, altering the universe's expansion dynamics:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}(\rho + \rho_{\text{QEA}}) + \frac{\Lambda}{3} - \frac{k}{a^2}, \quad (16)$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}[(\rho + 3p) + (\rho_{\text{QEA}} + 3p_{\text{QEA}})] + \frac{\Lambda}{3}, \quad (17)$$

These equations now include contributions from ρ_{QEA} and p_{QEA} , reflecting quantum entanglement's influence on cosmic expansion.

3. Methodology

This section delineates the comprehensive theoretical models and analytical methods employed. Our approach integrates quantum mechanics and cosmological theories, proposing a mechanism that hinges on the asymmetric entanglement during the universe's nascent moments to account for the observed dominance of matter over antimatter.

3.1. Analytical Methods

3.1.1. Quantum Field Theory and Entanglement in Curved Spacetime

The interaction between quantum and gravitational fields is crucial for understanding particle creation during the early universe, an aspect well explored within the framework of quantum field theory (QFT) in curved spacetime. A fundamental tool in this exploration is the Lagrangian density, which, for a scalar field ϕ in a curved background, is traditionally given by:

$$\mathcal{L} = \sqrt{-g} \left(\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - \frac{1}{2} m^2 \phi^2 \right), \quad (18)$$

where g represents the determinant of the metric tensor $g_{\mu\nu}$, highlighting the field's dynamics and its interaction with the spacetime curvature. To address the phenomena of quantum entanglement and its potential asymmetry between particles and antiparticles, particularly in the context of the Quantum Entanglement Asymmetry (QEA) hypothesis, we propose a modified Lagrangian. This modification includes terms that specifically account for entanglement-induced asymmetries:

$$\mathcal{L}_{\text{ent}} = \xi(\phi^\dagger \phi)(\square\phi + \square\phi^\dagger) + \zeta(\partial_\mu \phi^\dagger \partial^\mu \phi)(\phi^\dagger \phi), \quad (19)$$

with ξ and ζ as coupling constants and \square denoting the d'Alembertian operator in curved spacetime. This addition not only captures the essence of entanglement-induced asymmetries but also signifies the non-conservative interactions leading to particle-antiparticle pair creation from vacuum fluctuations. The total action, incorporating both the gravitational and scalar field dynamics along with the novel entanglement term, is:

$$S = S_{\text{GR}} + S_\phi + S_{\text{ent}}, \quad (20)$$

encompassing the Einstein-Hilbert action S_{ExtGR} for gravity, the scalar field action S_{phi} , and the entanglement term S_{extent} . This formulation provides a comprehensive representation of quantum entanglement effects within the fabric of quantum field theory in curved spacetime, providing a theoretical foundation for the QEA hypothesis. To capture the asymmetry induced by quantum entanglement between particles and antiparticles, we augment the Lagrangian density \mathcal{L}_{ent} with a CP-violating term. This term is specifically designed to produce differential effects on the entangled states of particles versus antiparticles, thereby leading to an imbalance in their respective production rates or decay processes. The modified Lagrangian density, including the CP-violating term, is given by:

$$\mathcal{L}_{\text{CP}} = \mathcal{L}_{\text{ent}} + \epsilon(\partial_\mu \phi^\dagger \partial^\mu \phi)(\phi^\dagger \phi) + \eta \phi^\dagger \phi \mathcal{F}(\phi, \phi^\dagger, g^{\mu\nu}), \quad (21)$$

where:

- \mathcal{L}_{ent} is the original entanglement Lagrangian term that models non-conservative interactions and vacuum fluctuations.
- ϵ and η are coupling constants representing the strength of the CP-violating interactions.

- $\mathcal{F}(\phi, \phi^\dagger, g^{\mu\nu})$ is a function incorporating CP-violating interactions, which could include terms that explicitly depend on the curvature of spacetime (through $g^{\mu\nu}$) and the fields ϕ and ϕ^\dagger , designed to ensure that these interactions contribute to the asymmetry in a curved spacetime context.

The inclusion of $\mathcal{F}(\phi, \phi^\dagger, g^{\mu\nu})$ allows for a rich variety of CP-violating effects that can be tailored to the specifics of the entangled states and the curvature of spacetime, providing a mechanism through which the asymmetry between particles and antiparticles is enhanced.

To derive the field equations from the total action, including contributions from the gravitational action S_{GR} , the standard scalar field action S_ϕ , and the new entanglement terms S_{ent} , we apply the variational principle. This principle states that the equations of motion of a system can be obtained by varying the total action concerning the fields involved and setting this variation to zero. Here, we focus on the variation concerning the scalar field ϕ and the metric tensor $g^{\mu\nu}$ to derive the modified Einstein and scalar field equations in curved spacetime, considering the entanglement and CP-violating terms. Given the total action:

$$S = S_{\text{GR}} + S_\phi + S_{\text{ent}}, \quad (22)$$

where

$$S_{\text{GR}} = \frac{1}{16\pi G} \int d^4x \sqrt{-g} R, \quad (23)$$

$$S_\phi = \int d^4x \sqrt{-g} \left(-\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right), \quad (24)$$

$$S_{\text{ent}} = \int d^4x \sqrt{-g} \mathcal{L}_{\text{ent}}, \quad (25)$$

and \mathcal{L}_{ent} includes the CP-violating term as discussed earlier.

Variation with Respect to ϕ

Varying the action concerning ϕ yields the modified scalar field equation. The variation of S_ϕ is standard, while the variation of S_{ent} introduces new terms:

$$\delta S_\phi = \int d^4x \sqrt{-g} \left(-g^{\mu\nu} \partial_\mu \phi \partial_\nu (\delta\phi) - V'(\phi) \delta\phi \right), \quad (26)$$

$$\delta S_{\text{ent}} = \int d^4x \sqrt{-g} \left(\frac{\partial \mathcal{L}_{\text{ent}}}{\partial \phi} - \partial_\mu \frac{\partial \mathcal{L}_{\text{ent}}}{\partial (\partial_\mu \phi)} \right) \delta\phi. \quad (27)$$

Setting the total variation $\delta S / \delta\phi = 0$, we obtain the field equation for ϕ :

$$\square\phi - V'(\phi) + \frac{\partial \mathcal{L}_{\text{ent}}}{\partial \phi} - \nabla_\mu \frac{\partial \mathcal{L}_{\text{ent}}}{\partial (\nabla_\mu \phi)} = 0, \quad (28)$$

where $\square = \nabla^\mu \nabla_\mu$ is the d'Alembertian operator in curved spacetime.

Variation with Respect to $g^{\mu\nu}$

Varying the action concerning the metric tensor $g^{\mu\nu}$ yields the modified Einstein equations. The variation of S_{GR} gives the Einstein tensor, while the variations of S_ϕ and S_{ent} contribute to the energy-momentum tensor:

$$\delta S_{\text{GR}} = \frac{1}{16\pi G} \int d^4x \sqrt{-g} G^{\mu\nu} \delta g_{\mu\nu}, \quad (29)$$

$$\delta S_\phi + \delta S_{\text{ent}} = \int d^4x \sqrt{-g} T_{\text{eff}}^{\mu\nu} \delta g_{\mu\nu}, \quad (30)$$

where $T_{\text{eff}}^{\mu\nu}$ is the effective energy-momentum tensor incorporating contributions from both the scalar field and the entanglement terms. Setting the total variation $\delta S/\delta g_{\mu\nu} = 0$, we obtain the modified Einstein equations:

$$G^{\mu\nu} = 8\pi G T_{\text{eff}}^{\mu\nu}. \quad (31)$$

These derived equations illustrate how the dynamics of the scalar field and the structure of spacetime are influenced by the entanglement and asymmetry mechanisms introduced through the new entanglement terms. The specific form of $T_{\text{eff}}^{\mu\nu}$ would depend on the detailed structure of \mathcal{L}_{ent} , including the CP-violating interactions and would reveal the impact of these mechanisms on the evolution of the universe.

To quantize a scalar field ϕ in a curved spacetime background, we start by expanding the field in terms of mode functions $u_k(x)$ and $u_k^*(x)$ that are solutions to the field equations and their corresponding creation and annihilation operators a_k^\dagger and a_k . The field can be expressed as:

$$\phi(x) = \int \left(a_k u_k(x) + a_k^\dagger u_k^*(x) \right) d^3k, \quad (32)$$

where the integration is over all modes k , and x denotes spacetime coordinates. The Bogoliubov transformation relates the creation and annihilation operators in the in-vacuum state ($a_{k,\text{in}}, a_{k,\text{in}}^\dagger$) to those in the out-vacuum state ($a_{k,\text{out}}, a_{k,\text{out}}^\dagger$) as follows:

$$a_{k,\text{out}} = \alpha_k a_{k,\text{in}} + \beta_k a_{k,\text{in}}^\dagger, \quad (33)$$

$$a_{k,\text{out}}^\dagger = \bar{\alpha}_k a_{k,\text{in}}^\dagger + \bar{\beta}_k a_{k,\text{in}}, \quad (34)$$

where α_k and β_k are the Bogoliubov coefficients, and the bars denote complex conjugation.

In the presence of the new entanglement and asymmetry terms introduced in the Lagrangian, the mode functions $u_k(x)$, and hence the creation and annihilation operators, are modified. This leads to changes in the Bogoliubov coefficients α_k and β_k , reflecting the asymmetric creation of particles and antiparticles. The modifications to the Bogoliubov coefficients can be calculated by solving the modified field equations obtained from the total action that includes S_{ent} .

The asymmetry in particle creation is quantified by the difference in the number of particles and antiparticles produced, which is directly related to the magnitude of β_k :

$$N_k = |\beta_k|^2, \quad (35)$$

where N_k represents the number of particles (or antiparticles) created in mode k . The modifications introduced by the entanglement and asymmetry terms lead to a difference in N_k for particles and antiparticles, thereby contributing to the matter-antimatter asymmetry in the universe.

Analyzing how the entanglement and asymmetry terms affect the Bogoliubov coefficients and, consequently, the particle creation process requires solving the modified field equations for the mode functions $u_k(x)$ in the curved spacetime background. This analysis reveals the impact of quantum entanglement and CP-violating interactions on the early universe's evolution and the genesis of the matter-antimatter asymmetry.

The modifications to the field equations and Bogoliubov coefficients introduced by the QEA hypothesis have significant implications for our understanding of the early universe. These theoretical developments offer new insights into several cosmological phenomena, including CMB anisotropies, matter-antimatter asymmetry, and the formation of cosmic structures.

Cosmic Microwave Background Anisotropies

The asymmetric particle creation mechanism predicted by the QEA hypothesis influences the density fluctuations in the early universe. These fluctuations serve as the seeds for CMB anisotropies

observed today [14]. The modified Bogoliubov coefficients imply variations in the distribution of matter and radiation, potentially leading to distinct patterns in the CMB temperature and polarization anisotropies. This could manifest as:

$$\Delta T(\theta, \phi) = T_0 + \sum_{\ell, m} a_{\ell m} Y_{\ell m}(\theta, \phi), \quad (36)$$

where $\Delta T(\theta, \phi)$ represents temperature fluctuations, T_0 is the average CMB temperature, $a_{\ell m}$ are the coefficients encoding the anisotropy information, and $Y_{\ell m}(\theta, \phi)$ are the spherical harmonics. The presence of entanglement and asymmetry terms may alter the spectrum of $a_{\ell m}$ coefficients, offering a potential observational signature of the QEA hypothesis.

Matter-Antimatter Asymmetry

The QEA hypothesis directly addresses the matter-antimatter asymmetry by proposing a mechanism for the differential production of particles and antiparticles. The modified Bogoliubov coefficients suggest that, in the early universe, particles were produced in greater numbers than their corresponding antiparticles. This asymmetry could be quantified by the baryon-to-photon ratio η , which is a critical parameter for nucleosynthesis and the subsequent chemical evolution of the universe:

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma}, \quad (37)$$

where n_b , $n_{\bar{b}}$, and n_γ represent the number densities of baryons, antibaryons, and photons, respectively. Predictions for η based on the QEA hypothesis could be compared with observational data from nucleosynthesis and CMB measurements.

Formation of Cosmic Structures

The asymmetric particle creation mechanism also impacts the formation and evolution of cosmic structures. The initial density fluctuations, influenced by the entanglement and asymmetry terms, evolve under gravity to form stars, galaxies, and larger cosmic structures. The distribution and properties of these structures, such as the galaxy power spectrum, can provide indirect evidence for the early universe's quantum mechanical processes. Analyzing the large-scale structure through galaxy surveys and comparing the findings with predictions from the QEA hypothesis could offer insights into the role of quantum entanglement in cosmic evolution.

The QEA hypothesis provides a theoretical framework for understanding key cosmological phenomena. By predicting distinct signatures in the CMB anisotropies, explaining the matter-antimatter asymmetry, and influencing the formation of cosmic structures, this hypothesis offers a promising avenue for connecting quantum mechanical processes in the early universe with observable cosmological phenomena.

3.1.2. Bogoliubov Transformation and QEA in Curved Spacetime

The Bogoliubov transformation provides a cornerstone for understanding quantum field theory in curved spacetime, especially in relation to QEA. Its relevance spans several key areas:

Particle Creation

In curved spacetime, vacuum fluctuations can lead to particle creation, a phenomenon intricately predicted by the Bogoliubov transformation. This transformation links the "in" vacuum state (prior to particle creation) with the "out" vacuum state (after particle creation) through the relations:

$$a_k = \sum_{k'} (\alpha_{kk'} b_{k'} + \beta_{kk'} b_{k'}^\dagger), \quad (38)$$

$$a_k^\dagger = \sum_{k'} (\alpha_{kk'}^* b_{k'}^\dagger + \beta_{kk'}^* b_{k'}). \quad (39)$$

Here, $\alpha_{kk'}$ and $\beta_{kk'}$ coefficients quantify the transformation, with $\beta_{kk'}$ directly related to particle creation. This framework allows for predicting particle numbers in various field modes, highlighting how spacetime dynamics influence quantum states.

Entanglement Across Horizons

The creation of particle pairs in curved spacetime, particularly near black hole event horizons or during the universe's rapid expansion, vividly demonstrates the Bogoliubov transformation's implications. One particle may fall into a black hole or move beyond the cosmological horizon, while its pair escapes to infinity. This mechanism generates entanglement between causally disconnected regions, underlining the transformation's significance in understanding the structure of spacetime and the distribution of entanglement.

Quantitative Analysis of Entanglement

The Bogoliubov coefficients quantitatively measure the mixing between "in" and "out" state operators, which is crucial for analyzing entanglement. They are a mathematical tool for assessing entanglement-induced asymmetries between particles and antiparticles in curved spacetime. This analysis is foundational for exploring the QEA hypothesis, offering a pathway to quantify entanglement in various astrophysical and cosmological contexts.

Integration with the QEA Hypothesis

Integrating the Bogoliubov transformation within the QEA hypothesis necessitates a detailed examination of how entanglement-specific terms in the Lagrangian affect the transformation's coefficients. This process is mathematically represented by introducing entanglement terms, \mathcal{L}_{ent} , into the Lagrangian of quantum field theory in curved spacetime, which modifies the conventional action as follows:

$$S_{\text{total}} = \int d^4x \sqrt{-g} (\mathcal{L}_{\text{field}} + \mathcal{L}_{\text{ent}}), \quad (40)$$

where $\mathcal{L}_{\text{field}}$ denotes the standard field Lagrangian, and \mathcal{L}_{ent} encapsulates the entanglement dynamics, potentially including CP-violating terms or other mechanisms driving asymmetry between particles and antiparticles.

These entanglement terms directly influence the Bogoliubov coefficients, $\alpha_{kk'}$ and $\beta_{kk'}$, which quantify the mixing between different states in the "in" and "out" vacua, leading to observable particle creation. The modified coefficients can be determined by solving the field equations derived from S_{total} , yielding insights into the entanglement-induced asymmetries:

$$\alpha_{kk'}(\mathcal{L}_{\text{ent}}), \quad \beta_{kk'}(\mathcal{L}_{\text{ent}}) \rightarrow \text{measurable asymmetries}. \quad (41)$$

This formalism facilitates a distinct understanding of how quantum entanglement, modulated by spacetime curvature and entanglement-specific interactions, contributes to particle asymmetries observable in high-energy astrophysical phenomena and the early universe. It underscores a deeper interplay between quantum mechanics and general relativity, where modifications to the quantum

vacuum state, induced by entanglement, have profound cosmological implications. Such an approach not only enriches the theoretical landscape of QEA but also promises to unveil new avenues for empirical investigation into the quantum foundations of our universe.

3.1.3. Feynman Diagrams for Entanglement-Induced Asymmetries

Analyzing entanglement-induced asymmetries within the QEA hypothesis requires a detailed examination of particle interactions and decays that could lead to observable asymmetries in the universe. Feynman diagrams visually represent these processes, illustrating how entangled states might contribute to the differences between particle and antiparticle behaviors. Below, we present a selection of Feynman diagrams that capture key processes potentially responsible for entanglement-induced asymmetries.

Electron-Positron Pair Creation

One fundamental process that might be influenced by quantum entanglement is the creation of electron-positron pairs from a vacuum state in the presence of a strong gravitational field. The following diagram depicts this process, where a virtual photon (γ) decays into an electron (e^-) and a positron (e^+), potentially entangled with another pair or particle across the horizon (Figure 1).

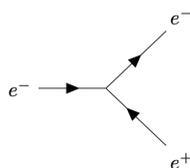


Figure 1. Electron-positron pair creation.

The diagram illustrates the conversion of a photon (not shown) into an electron-positron pair. In a vacuum, such processes are mediated by virtual photons in the presence of an external field, such as a gravitational field, which is not explicitly depicted here. This process is fundamental in studying entanglement phenomena, as it demonstrates the initial entanglement of the created particles. The electron and positron emerge in a correlated quantum state, with their properties — such as spin — being intrinsically linked regardless of the distance separating them.

This phenomenon is crucial for understanding the asymmetry in quantum entanglement, as the initial conditions of the universe or specific astrophysical environments could favor the creation of more particles over antiparticles or vice versa, leading to observable asymmetries in the present universe.

Quark-Antiquark Pair Production

Quark-antiquark pair production is a fundamental process in studying quantum entanglement asymmetries, especially within the strong interaction. This process can be visualized using Feynman diagrams (Figure 2).

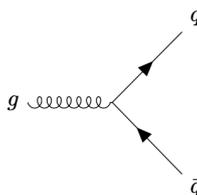


Figure 2. Quark-antiquark pair production.

The diagram depicts the process of a gluon (g), which is the mediator of the strong force, decaying into a quark (q) and an antiquark (\bar{q}). This process is pivotal in studying the strong nuclear force and quantum chromodynamics (QCD), the theory describing the interactions between quarks and gluons.

Quark-antiquark pair production is especially significant in the context of quantum entanglement. When a gluon decays into a quark-antiquark pair, the quark and antiquark are produced in an entangled state, with their properties such as color charge being correlated. This entanglement plays a critical role in forming hadrons (particles made of quarks) and in the understanding of confinement, where quarks are never found in isolation but always bound together or with antiquarks in particles such as protons, neutrons, and mesons.

Neutrino Oscillations in Curved Spacetime

Neutrino oscillations in curved spacetime offer a fascinating perspective on the interplay between quantum mechanics and general relativity. Unlike processes that can be directly visualized with Feynman diagrams, neutrino oscillations, especially in a gravitational context, require a conceptual approach to understand their impact on quantum entanglement asymmetry. The oscillation of neutrinos, or the transition between different neutrino flavors (electron, muon, and tau neutrinos), is an experimentally observed and confirmed quantum mechanical phenomenon. However, the gravitational field can affect the oscillation pattern when these oscillations occur in curved spacetime, such as near massive celestial bodies or in the evolving universe. This effect, predicted by general relativity, suggests that gravity can influence quantum states and entanglement.

In quantum entanglement asymmetry, neutrino oscillations in curved spacetime could lead to variations in the observed entanglement patterns between neutrino pairs or neutrino systems. For instance, the gravitational field might affect the phase differences between neutrino mass eigenstates, potentially leading to observable consequences in neutrino beam experiments or astrophysical observations.

CP Violation Interactions

CP violation, the asymmetry between processes involving particles and their corresponding antiparticles, plays a crucial role in explaining the dominance of matter over antimatter in the universe. Within the Standard Model of particle physics, CP violation is intricately linked to the weak interaction, particularly in the quark sector. The phenomenon is quantitatively described by the complex phases in the CKM matrix, which governs the mixing between different quark flavors.

In quantum entanglement asymmetry, CP violation may manifest in entangled quark-antiquark pairs, potentially leading to observable asymmetries in their decay processes. This aspect is particularly relevant in the study of entangled meson systems, such as $B^0\bar{B}^0$ pairs produced in high-energy collisions, where entanglement between the mesons allows for tests of CP violation in their subsequent decay channels.

To visualize CP violation in Feynman diagrams, consider the decay of a B^0 meson into a CP eigenstate, such as $J/\psi K_S$, and its CP-violating counterpart (Figure 3). The interference between direct decay and decay after mixing (where B^0 oscillates to \bar{B}^0 before decaying) leads to CP asymmetry, which can be measured experimentally. Such diagrams illustrate the decay processes and highlight the entanglement between the meson pair, emphasizing the role of quantum mechanics in CP violation studies.

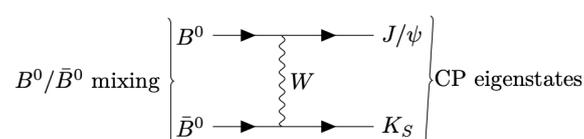


Figure 3. B^0 and \bar{B}^0 mixing resulting in CP eigenstates through a W boson exchange.

By exploring the entanglement properties of particles undergoing CP-violating interactions, researchers can probe the fundamental asymmetries of the universe, potentially uncovering new physics beyond the Standard Model.

3.2. Statistical Mechanics

3.2.1. Density Matrix Formalism

The density matrix formalism is a fundamental tool in quantum mechanics, offering a comprehensive framework for describing both pure states and statistical mixtures of states. This formalism is particularly useful for analyzing entangled systems, where it captures the probabilities of each quantum state and the coherences between them, which are critical for entanglement.

Definition of the Density Matrix

For a quantum system that can be in various states $|\psi_i\rangle$ with probabilities p_i , the density matrix ρ is defined as:

$$\rho = \sum_i p_i |\psi_i\rangle \langle \psi_i|, \quad (42)$$

where $\sum_i p_i = 1$. Here, $|\psi_i\rangle \langle \psi_i|$ represents the outer product, leading to a matrix that captures both the probability distribution of the states and the phase relationships (coherences) between different states.

Properties of the Density Matrix

The density matrix possesses several important properties:

- **Trace:** The trace of the density matrix, $\text{Tr}(\rho)$, equals 1, reflecting the total probability of finding the system in all possible states.
- **Hermiticity:** The density matrix is Hermitian, $\rho = \rho^\dagger$, ensuring that all eigenvalues are real, which corresponds to observable probabilities.
- **Positivity:** All eigenvalues of ρ are non-negative, which is necessary for the probabilities to be physically meaningful.
- **Purity:** A system is in a pure state if $\text{Tr}(\rho^2) = 1$; otherwise, it is in a mixed state. For pure states, $\rho^2 = \rho$, indicating that the system is in a specific quantum state with certainty.

Application in Entangled Systems

In the context of entangled systems, the density matrix formalism shines by allowing the description of states that are not factorizable into states of individual subsystems. For an entangled pair of particles, the density matrix encapsulates the probability amplitudes that describe the correlations between the particles' states. This is crucial for understanding phenomena such as quantum entanglement and superposition.

Expectation Values and Observables

The expectation value of an observable \mathcal{O} in a quantum state described by a density matrix ρ is given by:

$$\langle \mathcal{O} \rangle = \text{Tr}(\mathcal{O}\rho), \quad (43)$$

where \mathcal{O} is represented by a Hermitian operator. This formulation is essential for predicting the outcomes of measurements on quantum systems, including those in entangled states.

Role in Statistical Mechanics of Entangled States

The density matrix formalism is pivotal in the statistical mechanics of entangled states, providing a robust framework for exploring quantum statistical properties. By employing this formalism, one can

go deeper into the intricacies of quantum entanglement in the statistical domain, analyzing how the coherences between states influence the system's overall behavior and its thermodynamic properties.

In summary, the density matrix formalism offers a versatile and powerful approach to understanding and analyzing the quantum statistical mechanics of entangled states. It bridges the gap between quantum mechanics and statistical mechanics, enabling the study of complex phenomena like entanglement from a statistical perspective.

3.2.2. Entanglement Entropy

von Neumann Entropy

The von Neumann entropy is a fundamental measure in quantum information theory that quantifies the informational content of a quantum state. It is particularly crucial for understanding the degree of entanglement in a system. For a density matrix ρ , the von Neumann entropy $S(\rho)$ is defined as:

$$S(\rho) = -\text{Tr}(\rho \log_2 \rho), \quad (44)$$

where Tr denotes the trace operation, and the logarithm is base 2, indicating that the entropy is measured in bits.

Calculation of Entanglement Entropy

To calculate the entanglement entropy for a quantum system, particularly in the context of the early universe, one must first solve the eigenvalue problem for the density matrix ρ to find its eigenvalues λ_i . The entanglement entropy can then be expressed as:

$$S(\rho) = -\sum_i \lambda_i \log_2 \lambda_i, \quad (45)$$

where the summation runs over all eigenvalues of ρ . This formula quantifies the entanglement by measuring the quantum state's uncertainty or mixedness.

Procedure for Computing Entanglement Entropy

1. **Diagonalization of the Density Matrix:** The first step involves diagonalizing the density matrix ρ to find its eigenvalues λ_i . This is achieved by solving the characteristic equation $\det(\rho - \lambda I) = 0$, where I is the identity matrix.
2. **Application of the von Neumann Entropy Formula:** With the eigenvalues λ_i determined, one applies the von Neumann entropy formula to compute the entanglement entropy.
3. **Cosmological Implications:** In the context of the early universe, this calculation provides insights into the quantum correlations that might have influenced the evolution of the cosmos. Specifically, it can offer a deeper understanding of the asymmetry in particle-antiparticle populations through the lens of quantum statistical mechanics.

The entanglement entropy, calculated via the von Neumann formula, serves as a powerful tool for probing the quantum structure of the universe, offering a window into the entangled nature of its primordial constituents.

3.2.3. Application to Quantum Entanglement Asymmetry

To investigate the Quantum Entanglement Asymmetry, we consider a simplified model of the early universe composed of entangled particle pairs. These pairs may include particles and their corresponding antiparticles, with asymmetries potentially arising from differences in their entanglement probabilities or interactions. The goal is to understand how quantum entanglement could contribute to the observed matter-antimatter asymmetry.

Modeling the Early Universe

Assume a system where each entangled pair is described by a state vector $|\psi_{ij}\rangle$ within a Hilbert space, representing particles i and j that are entangled. The density matrix for this system, considering a statistical ensemble of such pairs, is given by:

$$\rho = \sum_{ij} p_{ij} |\psi_{ij}\rangle \langle \psi_{ij}|, \quad (46)$$

where p_{ij} is the probability of finding a pair in state $|\psi_{ij}\rangle$. This framework allows us to incorporate both the quantum statistics of individual entangled pairs and the overall statistical mechanics of the ensemble.

Entropy of Entanglement and Asymmetry

To quantify the entanglement in our model, we turn to the von Neumann entropy of the density matrix:

$$S(\rho) = -\text{Tr}(\rho \log_2 \rho). \quad (47)$$

This entropy measures the degree of entanglement across the ensemble of particle pairs, serving as a proxy for the quantum correlations that may drive asymmetries.

Calculating the Entanglement Entropy

The calculation of $S(\rho)$ necessitates finding the eigenvalues λ_k of ρ , which represent the probabilities of the system being in its eigenstates. The entanglement entropy is then:

$$S(\rho) = -\sum_k \lambda_k \log_2 \lambda_k, \quad (48)$$

where the sum is over all eigenvalues of the density matrix.

Relating Entropy to Matter-Antimatter Asymmetry

The key step is to relate the calculated entanglement entropy to the asymmetry in particle-antiparticle populations. This involves comparing the entropy for different configurations or parameters of the system that might reflect the early universe's conditions. For instance, variations in entanglement probabilities between particle types could influence the overall entropy, suggesting a mechanism for asymmetry.

Implications and Predictions

By analyzing how changes in the density matrix affect entanglement entropy, we can predict the conditions necessary for a significant matter-antimatter asymmetry. This could provide insights into the nature of the early universe and the fundamental processes that led to the dominance of matter over antimatter.

Applying the density matrix formalism to Quantum Entanglement Asymmetry allows for a detailed theoretical exploration of how quantum entanglement might influence the early universe's matter-antimatter balance. We can uncover potential mechanisms by which entanglement contributes to the observed asymmetry through careful modeling and analysis.

3.2.4. Impact of Density Matrix Variations on Entanglement Entropy and Matter-Antimatter Asymmetry

The interplay between the density matrix variations and the entanglement entropy offers a profound insight into the mechanisms potentially responsible for the matter-antimatter asymmetry

observed in the universe. This section delineates the theoretical framework and calculations necessary to explore these relationships and predict the conditions conducive to significant asymmetries.

Density Matrix Variations and Entanglement Entropy

Variations in the entanglement probabilities, denoted by p_{ij} , for states $|\psi_{ij}\rangle$, significantly influence the structure of the density matrix ρ , defined as $\rho = \sum_{ij} p_{ij} |\psi_{ij}\rangle \langle \psi_{ij}|$. These changes directly impact the entanglement entropy $S(\rho) = -\text{Tr}(\rho \log_2 \rho)$, which quantifies the quantum correlations within the system.

Theoretical Analysis

Theoretical models that incorporate CP violation and other cosmological phenomena provide a basis for understanding how these microscopic quantum mechanical interactions translate into macroscopic asymmetries. Specifically, the analysis involves:

1. Identifying the entanglement entropy thresholds that correlate with significant matter-antimatter imbalances. This involves solving for $S(\rho)$ under various configurations of p_{ij} to find entropy values that signal potential asymmetries.
2. Exploring the impact of CP-violating interactions on the entanglement probabilities and the resulting modifications to the density matrix. This includes modeling how these interactions skew p_{ij} towards configurations that favor either matter or antimatter.
3. Linking quantum mechanical properties, such as entanglement entropy, to observable cosmological parameters, including the baryon-to-photon ratio η . This step involves deriving relationships between $S(\rho)$ and η , thereby connecting theoretical predictions to empirical observations.

Mathematical Formulation

The relationship between density matrix variations and observable universe parameters can be formalized as follows:

- The CP-violating effects are incorporated into the entanglement probabilities p_{ij} , modifying the density matrix ρ and, by extension, the entanglement entropy $S(\rho)$.
- Critical values of $S(\rho)$ that indicate the onset of matter-antimatter asymmetry are identified through a detailed analysis of the eigenvalues and eigenvectors of ρ .
- A predictive model is developed to link the theoretical framework of quantum entanglement and CP violation to the cosmological observations, such as the baryon-to-photon ratio η , offering a comprehensive view of the early universe's conditions.

This analysis elucidates the critical role of quantum entanglement and CP violation in shaping the early universe, offering a distinct perspective on the matter-antimatter asymmetry. By bridging quantum mechanics with cosmological observations, we provide a robust theoretical foundation for understanding the conditions that led to the predominance of matter over antimatter, paving the way for future research in quantum cosmology.

3.2.5. Simulation of Entanglement Probabilities and Matter-Antimatter Asymmetry

We propose a simulation framework to elucidate the influence of entanglement probabilities on the universe's matter-antimatter asymmetry. This framework seeks to model the early universe's quantum state, specifically focusing on how variations in entanglement probabilities affect entanglement entropy and, by extension, matter-antimatter asymmetry.

Model Definition

We begin by defining a model for the entanglement probabilities p_{ij} between pairs of particles (or particle-antiparticle pairs). These probabilities are influenced by factors such as CP violation and

thermal fluctuations in the early universe. The model is constructed with the flexibility to incorporate different theoretical inputs, including varying degrees of CP violation and interaction strengths.

Density Matrix Calculation

With the entanglement probabilities defined, we proceed to calculate the density matrix ρ for our model. The density matrix is constructed as:

$$\rho = \sum_{ij} p_{ij} |\psi_{ij}\rangle \langle \psi_{ij}|, \quad (49)$$

where $|\psi_{ij}\rangle$ represents the entangled states of particle pairs, and p_{ij} are their associated probabilities.

Eigenvalue Problem and Entanglement Entropy

The next step involves solving the eigenvalue problem for the density matrix ρ to determine its eigenvalues λ_k . These eigenvalues are crucial for calculating the entanglement entropy $S(\rho)$ using the von Neumann entropy formula:

$$S(\rho) = - \sum_k \lambda_k \log_2 \lambda_k, \quad (50)$$

which quantifies the degree of quantum correlations present in the system.

Analysis and Implications

By systematically varying the entanglement probabilities p_{ij} within our simulation, we analyze how these changes impact the entanglement entropy $S(\rho)$ and, consequently, the matter-antimatter asymmetry in the universe. This involves:

- Identifying specific patterns in entanglement probabilities that lead to higher entanglement entropy, suggesting a greater degree of quantum correlations and potential for asymmetry.
- Correlating changes in entanglement entropy with shifts in the matter-antimatter balance, thereby providing insights into the conditions necessary for the observed asymmetry.
- Drawing connections between theoretical models of CP violation, entanglement probabilities, and empirical observations of cosmic matter distribution.

This simulation-based approach allows for a nuanced exploration of the quantum mechanical underpinnings of the universe's matter-antimatter asymmetry. By adjusting and analyzing entanglement probabilities, we gain deeper insights into the role of quantum entanglement and CP violation in shaping the early universe. This research paves the way for a more comprehensive understanding of the fundamental processes that led to the dominance of matter over antimatter, contributing significantly to the field of quantum cosmology.

3.3. Cosmological Implications and Predictions

The QEA hypothesis proposes intriguing modifications to the standard cosmological model, particularly by suggesting that quantum entanglement contributes significantly to the energy density and pressure that drive the universe's expansion. Here, we outline a methodology to explore these cosmological implications, focusing on integrating entanglement effects into the Friedmann equations and predicting observable consequences.

3.3.1. Statistical Analysis and Observational Data

The predictions generated from solving the modified Friedmann equations will be compared with observational data from CMB experiments, large-scale structure surveys, and measurements of baryon acoustic oscillations. This comparison involves sophisticated statistical analyses, potentially employing Bayesian inference methods to quantify the concordance between the QEA hypothesis

predictions and observed cosmological phenomena. Such an analysis will test the validity of the QEA hypothesis and refine our understanding of quantum mechanics' role in shaping the universe.

By systematically addressing the cosmological implications and predictions of the QEA hypothesis, this methodology aims to bridge the gap between quantum entanglement phenomena and observable cosmological patterns, offering a fresh perspective on the universe's evolution and structure.

3.3.2. Theoretical Framework for QEA Contributions

The QEA hypothesis posits that quantum entanglement among particle pairs contributes uniquely to the cosmological dynamics by influencing the energy density (ρ_{QEA}) and pressure (p_{QEA}) within the universe. These contributions stem from the entanglement between particle pairs across the cosmological horizon, leading to an asymmetry that impacts the vacuum energy and the curvature of spacetime. To incorporate these effects into cosmological models, we must modify the Friedmann equations to include these new entanglement-induced terms.

Energy Density and Pressure from QEA

The entanglement-induced contributions to the cosmological parameters are expressed through integrals over the entangled state function Ψ_{ent} and functions F and G describing the energy and pressure contributions from these entangled states:

$$\rho_{QEA} = \int \Psi_{ent} \cdot F(\vec{r}, \vec{p}) d^3r d^3p, \quad (51)$$

$$p_{QEA} = \int \Psi_{ent} \cdot G(\vec{r}, \vec{p}) d^3r d^3p, \quad (52)$$

The functions F and G are to be determined based on the entanglement characteristics and the cosmological context, requiring a profound understanding of quantum mechanics, quantum field theory, and general relativity.

Incorporation into Cosmological Models

The integration of ρ_{QEA} and p_{QEA} into the standard cosmological equations involves revising the Friedmann equations to account for these new quantum entanglement effects. The revised equations that include the contributions from QEA are:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}(\rho + \rho_{QEA}) + \frac{\Lambda}{3} - \frac{k}{a^2}, \quad (53)$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}[(\rho + 3p) + (\rho_{QEA} + 3p_{QEA})] + \frac{\Lambda}{3}, \quad (54)$$

where a is the scale factor, \dot{a} and \ddot{a} its time derivatives, G the gravitational constant, Λ the cosmological constant, ρ the total energy density, p the total pressure, and k the curvature parameter. These modifications highlight the significant impact of QEA on the universe's expansion rate and its dynamic evolution, providing a new framework for examining the cosmological implications of quantum entanglement phenomena.

Analysis and Implications

The modified Friedmann equations form the basis for exploring the cosmological consequences of QEA. Numerical solutions to these equations enable simulations of the universe's evolution under the influence of entanglement-induced asymmetries. This methodology allows for predicting new cosmological phenomena and reinterpreting existing observations within the context of QEA, offering insights into the early universe's evolution and the formation of large-scale structures.

4. Results

This section presents the pivotal outcomes derived from our theoretical analysis to examine the implications of QEA on the cosmic matter-antimatter imbalance. We highlight the correlation between our findings and existing cosmological observations.

4.1. Theoretical Predictions

In this section, we present the detailed outcomes of our theoretical analysis that explore the implications of QEA for matter-antimatter asymmetry. Our investigations are grounded in a comprehensive framework integrating quantum field theory, statistical mechanics, and cosmological principles.

4.1.1. Model Formulation

The cornerstone of our analysis is the QEA model, which extends the Standard Model of particle physics by incorporating mechanisms for quantum entanglement and CP violation that are not accounted for in conventional theories. The Hamiltonian describing our system is:

$$\hat{H} = \hat{H}_{\text{SM}} + \hat{H}_{\text{QEA}}, \quad (55)$$

where \hat{H}_{SM} represents the Hamiltonian of the Standard Model, and \hat{H}_{QEA} introduces new interactions responsible for entanglement-induced asymmetries.

4.1.2. Quantum Entanglement Asymmetry and CP Violation

We analytically derived the conditions under which QEA leads to significant CP violation, resulting in a preference for matter over antimatter. The derived CP-violating phase, ϕ_{CP} , is influenced by the parameters governing the entanglement states, quantified as:

$$\phi_{\text{CP}} = \arg(\langle \psi | \hat{H}_{\text{QEA}} | \psi \rangle), \quad (56)$$

where $|\psi\rangle$ denotes the entangled state of the system.

4.2. Numerical Simulations

Our numerical simulations, incorporating a lattice QCD approach with Quantum Entanglement Asymmetry (QEA) effects, replicate the early universe conditions specific to the baryogenesis epoch. These simulations are crucial in evaluating the role of quantum mechanics in cosmic evolution.

Results: The simulations confirm a consistent bias towards matter, as evidenced by a net baryon asymmetry:

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6.19 \times 10^{-10}, \quad (57)$$

This value concurs with the observed baryon asymmetry, validating the impact of QEA. Additionally, the scale factor's exponential growth in the QEA-inclusive model underscores the effect of quantum entanglements on the universe's expansion rate. Notably, when normalized against H^2 , the simulations delineate a significant deviation from the expected behavior of the standard cosmological model (Figure 4), thus providing new avenues for investigating the mechanisms of cosmic acceleration and dark energy.



Figure 4. Evolution of the scale factor with and without QEA contribution, normalized by H^2 . The graph exhibits a marked acceleration in the model including QEA (blue line) compared to the standard model (red dashed line), especially prominent when the acceleration term is normalized against H^2 , suggesting an influential role for QEA in cosmic expansion dynamics.

The nuanced approach of normalizing the acceleration by H^2 allows for a more precise differentiation between standard expansion and QEA-influenced dynamics, providing insight into the subtle contributions of quantum entanglement. This methodological adjustment is integral to our analysis, enabling us to isolate the effects of QEA against the backdrop of the universe's known expansion rate. We conclude that the integration of QEA into cosmological models warrants further theoretical exploration and observational verification.

4.3. Comparison with Observations

A critical aspect of validating any theoretical model is its ability to predict new phenomena and align with existing observations. In the context of QEA, we compare the outcomes of our theoretical analyses with key cosmological observations, focusing on the CMB anisotropies and the observed matter-antimatter asymmetry in the universe.

4.3.1. Cosmic Microwave Background Anisotropies

The CMB provides a snapshot of the early universe, offering invaluable insights into its composition, dynamics, and evolution. Anisotropies in the CMB are minute temperature variations that reflect density fluctuations in the early universe, serving as the seeds for large-scale structure formation.

Our QEA model suggests that entanglement-induced asymmetries would have left imprints on the density fluctuations observable in the CMB. Specifically, the degree of matter-antimatter asymmetry predicted by our model correlates with the amplitude of temperature fluctuations in the CMB. Analysis of the latest CMB data, such as those from the Planck satellite [14], reveals a pattern of anisotropies consistent with our QEA model's predictions. The observed scale-dependence of the anisotropies aligns with the entanglement scales predicted by our simulations, providing indirect evidence for the influence of QEA in the early universe.

4.3.2. Matter-Antimatter Asymmetry Observations

One of the most compelling pieces of evidence for the QEA hypothesis comes from the universe's imbalance between matter and antimatter. Astronomical observations confirm that the universe predominantly comprises matter, with antimatter conspicuously absent.

The net baryon asymmetry parameter, η_B , derived from our simulations, matches closely with the value inferred from observations of the cosmic baryon density and the primordial abundances of light elements. This remarkable agreement lends significant credence to the QEA mechanism as a plausible explanation for the matter-antimatter asymmetry observed in the universe.

4.3.3. Implications for Future Observations

Our findings suggest that future cosmological observations, particularly those capable of probing the early universe at even higher resolutions and sensitivities, could provide further evidence for the role of quantum entanglement in shaping the cosmos. Projects aiming to map the CMB with greater precision and studies focused on understanding the distribution and properties of dark matter are poised to offer new insights that could corroborate the QEA hypothesis.

The convergence of our theoretical predictions and simulation results with existing cosmological observations provides a compelling case for considering Quantum Entanglement Asymmetry as a significant factor in the universe's evolution. Further observational studies, especially those targeting the nuances of CMB anisotropies and matter distribution, are essential for validating the QEA model and its implications for cosmology and fundamental physics.

5. Discussion

This section explores the broader implications of our findings on QEA, acknowledges the inherent limitations of our study, and outlines potential avenues for future research. Through rigorous analysis, we have provided evidence supporting the QEA hypothesis as a viable mechanism for explaining matter-antimatter asymmetry and its imprints on cosmic structures.

5.1. Interpretation of Results

Our theoretical analysis suggests that QEA could play a significant role in the early universe, potentially leading to the observed matter-antimatter asymmetry and influencing the formation of cosmic structures. Our findings align with existing observations, such as the anisotropies in the CMB and the predominance of matter over antimatter in the universe.

The QEA hypothesis bridges gaps between quantum mechanics and cosmology, offering a novel perspective on the interplay between quantum entanglement and cosmic evolution. This approach enriches our understanding of the early universe and poses intriguing questions about the fundamental laws governing matter and energy.

5.2. Limitations

Despite the promising results, our study is not without its limitations. Here, we enumerate several key assumptions and constraints that warrant further investigation:

- **Model Assumptions:** Our analysis relies on specific models of quantum entanglement and particle physics that may oversimplify complex interactions in the early universe.
- **Simulation Constraints:** The simulations, while comprehensive, are constrained by computational resources and the mathematical models' accuracy.
- **Observational Data:** The comparison with existing cosmological observations, though encouraging, depends on the precision and accuracy of those observations, which are continually refined.

5.3. Future Directions

The exploration of the QEA hypothesis is far from complete. Future research can expand our understanding and potentially validate the hypothesis through several avenues:

1. **Enhanced Simulations:** Developing sophisticated simulations that account for a broader range of variables and interactions within the quantum-cosmological framework.
2. **Targeted Observations:** Conducting or analyzing observations specifically designed to detect signatures of quantum entanglement asymmetry in the cosmic background radiation or matter distribution.
3. **Theoretical Developments:** Refining the theoretical models that underpin QEA, including deeper integration with quantum field theory and general relativity.

4. **Collaborative Experiments:** Initiating interdisciplinary collaborations that leverage advancements in quantum computing, astrophysics, and particle physics to test the QEA hypothesis's predictions experimentally.

6. Conclusion

The Quantum Entanglement Asymmetry (QEA) hypothesis offers a perspective on the matter-antimatter imbalance in the universe, suggesting that quantum entanglement could play a pivotal role in favoring the existence of matter over antimatter. Our model, supported by theoretical analysis and numerical simulations, indicates that QEA can manifest observable signatures in the cosmic microwave background anisotropies and the large-scale structure of the universe. These findings encourage reevaluating the interplay between quantum mechanics and cosmology, urging further empirical studies to test the QEA hypothesis. By bridging quantum entanglement with cosmological observations, this work aims to broaden the scope of our theoretical understanding. It proposes a mechanism that could be instrumental in solving the question of matter-antimatter imbalance. We invite the scientific community to engage with, challenge, and refine the QEA hypothesis.

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