Matter–Antimatter Resonances in Unified Fractal Quantum Field Theory (UFQFT): Fractal Phase Inversions, Stability Asymmetries, and the Origin of Baryogenesis

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Abstract

In this paper, we investigate the origin of matter–antimatter asymmetry within the framework of the Unified Fractal Quantum Field Theory (UFQFT). Unlike the Standard Model, where antiparticles are introduced as independent states with opposite quantum numbers, UFQFT interprets them as phase-inverted resonance modes of the same underlying fractal configuration of the energy (Φ) and charge (Ψ) fields. We show that the distinction between a particle and its antiparticle arises not from mass or spin differences, but from a π-shift in the fractal resonance phase. This perspective naturally embeds charge duality and matter–antimatter duality into the same geometric foundation. Furthermore, small deviations in the fractal dimension (ΔD) lead to differences in resonance stability between matter and antimatter states, which provides a geometric mechanism for baryon asymmetry. We discuss how this framework relates to CP violation, Sakharov's conditions, and the phenomenology of baryogenesis. Finally, we explore cosmological implications, including possible links to dark matter and dark energy, as well as observational and experimental avenues for testing the model.

Keywords: UFQFT; matter–antimatter asymmetry; fractal resonance; phase inversion; CP violation; baryogenesis; fractal dimension; particle stability; cosmology; dark matter

Introduction

Research on the origin of the cosmic matter–antimatter imbalance has followed several complementary lines since Sakharov's foundational statement of the necessary conditions for baryogenesis (Sakharov, 1967). The Standard-Model source of CP violation was formalized in the Kobayashi–Maskawa mechanism (Kobayashi & Maskawa, 1973), which demonstrated how quark-mixing phases can produce CP-odd effects in weak interactions but is generally understood to be insufficient by itself to explain the observed baryon asymmetry. From these bases, three principal baryogenesis scenarios have been developed and extensively reviewed in the literature: electroweak baryogenesis (Riotto & Trodden, 1999), thermal leptogenesis originating from the out-of-equilibrium decays of heavy Majorana neutrinos (Fukugita & Yanagida, 1986; Buchmüller et al. 2005), and supersymmetric scalar-field mechanisms such as the Affleck–Dine scenario (Affleck & Dine, 1985). Precision cosmology (Aghanim 2018) fixes the baryon-to-photon ratio and tightly constrains model parameter space, providing a quantitative target ($\eta \sim 6\times10^{-10}$) for any proposed mechanism.Independently, theoretical work on nonstandard spacetime structure — including fractal or scale-dependent effective dimensions — has matured in parallel: several approaches (scale-relativity, causal dynamical triangulations, and fractal-field constructions) report scale-dependent spectral/Hausdorff dimensions and suggest that ultraviolet dimensional reduction or an effective fractal measure can modify field dynamics at early times (Nottale 2005; Ambjørn 2005; Calcagni 2010). These fractal/spacetime-dimension results provide a conceptual bridge to geometric resonance-based models (which aim to link CP-violating phase structure and resonance stability to spacetime microstructure) and motivate exploring baryogenesis as a consequence of scale-dependent geometric effects rather than—or in addition to—only particle-physics couplings.

Recent developments in Unified Fractal Quantum Field Theory (UFQFT) have extended the matter–antimatter problem into a geometric–resonance framework. Several studies propose that all fundamental particles emerge as resonant structures of unified energy–charge fields in fractal spacetime (Sogukpinar, 2025a). The pre–Big Bang fractal sea of coupled Φ_0–Ψ_0 fields has been suggested as a common origin of matter, dark matter, and cosmic inflation (Sogukpinar, 2025b), while subsequent works reinterpret proton spin structure (Sogukpinar, 2025c) and extend UFQFT to dark matter and dark energy as neutral fractal resonances (Sogukpinar, 2025d). Additional contributions address the arrow of time (Sogukpinar, 2025e), gravity as an emergent fractal symmetry (Sogukpinar, 2025f), and the hierarchy of elementary particles (Sogukpinar, 2025h). Applications include nuclear structure (Sogukpinar, 2025k;2025l), cosmology (Sogukpinar,2025m; 2025n), and astrophysical objects such as neutron stars and black holes (Sogukpinar, 2025p;2025r). More recent studies analyze baryonic properties (Sogukpinar, 2025s), high-energy collision phenomenology (Sogukpinar, 2025t), and the resonance origin of charge itself (Sogukpinar, 2025u). Taken together, this corpus outlines a coherent attempt to unify microphysical particle properties with large-scale cosmological evolution through fractal spacetime dynamics.

This paper proposes that, in UFQFT, antimatter is a phase-inverted resonance of the same fractal energy–charge structure as matter. Matter–antimatter distinction arises from a π-phase shift rather than differences in mass or spin, while small variations in fractal dimension (ΔD) create stability differences that can explain baryon asymmetry. The framework naturally incorporates CP violation and offers connections to dark matter, dark energy, and testable cosmological phenomena.

2. Foundations of UFQFT

2.1 Energy Field (Φ) and Charge Field (Ψ) Definitions

In the Unified Fractal Quantum Field Theory (UFQFT), all elementary excitations are described as resonances of two fundamental fields: the energy field (Φ) and the charge field (Ψ). The energy field defines the oscillatory backbone of particle structures, while the charge field encodes the directional asymmetry responsible for interaction properties. Formally, a resonance mode R is defined as a coupled configuration of Φ and Ψ,

$$R(x,t) = \Phi(x,t)\, e^{i\Psi(x,t)} \tag{1}$$

Where, Φ(x,t)= real-valued scalar energy density distribution, Ψ(x,t) = phase function associated with charge orientation. This dual-field representation ensures that energy and charge are not independent entities but rather projections of the same fractal resonance structure.

2.2 Fractal Spacetime Geometry and Dimension (D)

Unlike the Standard Model, which assumes a smooth four-dimensional manifold, UFQFT postulates that spacetime itself possesses a fractal effective dimension D, typically close to but not exactly 3. This fractal geometry governs the scaling of resonance modes and their stability. The measure of a spatial volume in UFQFT is expressed as

$$V_D(r) = \frac{\pi^{D/2}}{\Gamma(D^2+1)}\, r^D \tag{2}$$

Where, D = fractal dimension of spacetime, r = radial scale parameter, Γ(z) = Gamma function. For D=3, the conventional Euclidean volume is recovered, while deviations from 3 introduce stability and decay asymmetries in particle–antiparticle systems.

2.3 Resonance Configurations as Particle Definitions

In UFQFT, a particle is not treated as a pointlike object but as a stable resonance configuration of Φ and Ψ within fractal spacetime. The resonance condition can be expressed as a quantization rule over closed trajectories in phase space:

$$\oint \Psi \, d\Phi = 2\pi n\hbar, \tag{3}$$

Where, $n \in Z_n$ = resonance quantum number, $\hbar$ = reduced Planck constant. This relation ensures that only discrete resonance states are physically realized, naturally leading to the spectrum of elementary particles.

2.4 Charge Duality as ± Resonance Pairs

Electric charge emerges as a dual property of the charge field **(Ψ)** through symmetric and antisymmetric orientations. The fundamental duality is expressed as

$$\Psi \pm (x,t) = \pm \Psi(x,t), \tag{4}$$

corresponding to the particle–antiparticle charge conjugation. Accordingly, positive and negative charges represent phase-inverted resonance modes of the same underlying structure. The effective observable charge q can be defined as a projection of the Ψ-field over the fractal resonance mode:

$$q = \alpha_D \int \Psi(x,t) \, dV_D, \tag{5}$$

Where, α_D = normalization constant dependent on fractal dimension D, dV_D = differential volume element in fractal spacetime (from Eq. 2). This formulation demonstrates that charge is not a fundamental input but an emergent resonance property within UFQFT.

3. Antiparticles as Phase-Inverted Resonances

3.1 Concept of Phase Inversion in Fractal Resonance Space

In UFQFT, antiparticles are not introduced as independent fields but rather as phase-inverted resonance modes of the same underlying configuration of the energy field (Φ) and charge field (Ψ). If a particle resonance is represented by

$$R(x,t) = \Phi(x,t) \, e^{+i\Psi(x,t)} \tag{6}$$

then its corresponding antiparticle resonance is obtained through a π-shift (phase inversion):

$$\bar{R}(x,t) = \Phi(x,t) \, e^{-i\Psi(x,t)}. \tag{7}$$

Here, R(x,t) = particle resonance function, $\bar{R}(x,t)$ = antiparticle resonance function, Ψ(x,t) = charge-field phase, whose inversion corresponds to charge conjugation, Φ(x,t) = scalar energy field amplitude. Thus, the particle–antiparticle relation is a simple resonance conjugation:

$$\bar{R}(x,t) = R^*(x,t) \tag{8}$$

3.2 Electron–Positron System as a Case Study

The electron (e^-) resonance is defined by a stable configuration of Φ and Ψ with a negative charge projection:

$$q_{e^-} = -\alpha_D \int \Psi(x,t) \, dV_D \tag{9}$$

By applying the phase inversion (Eq. 7), the positron (e^+) resonance is obtained with opposite charge:

$$q_{e^+} = +\alpha_D \int \Psi(x,t)\, dV_D \tag{10}$$

Here, q_{e^-},q_{e^+} = charges of electron and positron, α_D = fractal normalization constant (depends on dimension D), dV_D = fractal volume element from Eq. (2). The electron–positron pair thus emerges as a phase-conjugate resonance doublet in UFQFT.

3.3 Quark–Antiquark Resonances and Meson Construction

Quarks are also defined as fractal resonance states with fractional charge values. For a quark resonance q, the antiparticle (antiquark $\bar{q}$) is given by:

$$R_q(x,t) = \Phi_q(x,t)\, e^{+i\Psi q(x,t)}, R_{\bar{q}}(x,t) = \Phi_q(x,t)\, e^{-i\Psi q(x,t)} \tag{11}$$

The construction of a meson corresponds to the superposition of a quark–antiquark pair,

$$M(x,t) = R_q(x,t) + R_{\bar{q}}(x,t) \tag{12}$$

which leads to cancellation of their charge phases:

$$\Psi_q(x,t) + \Psi_{\bar{q}}(x,t) = 0. \tag{13}$$

Thus, mesons are interpreted as neutralized resonance composites, stable due to the π-shift symmetry between quark and antiquark fields.

3.4 General Rule: Matter–Antimatter Duality as π-Shifted Resonance Modes

In general, the UFQFT prescription for matter–antimatter duality is given by:

$$R_{matter}(x,t) = \Phi(x,t)\, e^{+i\Psi(x,t)}, R_{antimatter}(x,t) = \Phi(x,t)\, e^{i(\Psi(x,t)+\pi)}. \tag{14}$$

Since

$$e^{i(\Psi+\pi)} = -e^{i\Psi} \tag{15}$$

the antimatter state is effectively the π-phase shifted version of the matter state. This makes antiparticles the resonance reflections of particles, embedded in the same fractal geometry.

4. Fractal Stability Asymmetries

4.1 The Role of Fractal Dimension (D) in Particle Stability

In UFQFT, the stability of a particle resonance is determined by the effective fractal dimension D of the underlying spacetime geometry. A resonance remains stable if its oscillatory mode is compatible with the embedding dimension of the fractal vacuum. The stability condition can be expressed as

$$\Gamma(D) \propto exp[-\beta\, (D_c - D)^2] \tag{16}$$

Where, $\Gamma(D)$ = resonance lifetime (stability factor), D = effective fractal dimension of the local spacetime, D_c = critical resonance dimension for maximum stability, β = scaling constant controlling sensitivity to dimensional deviation. Thus, particles whose fractal dimension D is closer to Dc will exhibit enhanced stability, while those with larger deviations decay more rapidly.

4.2 ΔD as the Source of Asymmetric Decay Probabilities

The asymmetry between matter and antimatter arises because their fractal resonance configurations differ slightly in D. We define the difference as

$$\Delta D = D_{matter} - D_{antimatter}. \tag{17}$$

This small shift produces an exponential bias in their relative decay probabilities. The ratio of decay rates is given by

$$\frac{\Gamma_{matter}}{\Gamma_{antimatter}} = exp[-\beta((D_c - D_{matter})^2 - (D_c - D_{antimatter})^2)]. \tag{18}$$

If $\Delta D \neq 0$ the symmetry is broken, leading to a preferential survival of one species over the other. Even a tiny difference $|\Delta D| \sim 10^{-6}|$ can be sufficient to explain the observed baryon asymmetry of the Universe.

4.3 Geometric Origin of Baryon Asymmetry

The baryon-to-antibaryon ratio observed in cosmology can therefore be attributed to the fractal geometric bias of resonance states. We define the baryon asymmetry parameter η as

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}, \tag{19}$$

Where, n_B = number density of baryons, $n_{\bar{B}}$ = number density of antibaryons, n_γ = photon number density (used as normalization). In UFQFT, η originates directly from the ΔD-induced asymmetry in stability,

$$\eta \propto f(\Delta D) = tanh(\kappa\, \Delta D) \tag{20}$$

with:κ = proportionality constant linking fractal deviation to cosmological number densities. Thus, the observed excess of matter over antimatter is interpreted as the macroscopic outcome of a microscopic fractal resonance imbalance, rooted in the fundamental geometry of spacetime.

5. Connection to CP Violation

The Unified Fractal Quantum Field Theory (UFQFT) naturally connects the phenomenon of CP violation to the geometric and resonance-based structure of particles and antiparticles. In this framework, the asymmetry arises from two complementary mechanisms: (i) dynamic phase shifts in resonance transitions, and (ii) static stability differences encoded in the fractal dimension. Together, they provide a unified explanation for Sakharov's conditions of baryogenesis.

5.1 CP violation as dynamic resonance phase shifts

In UFQFT, every particle state is described by a resonance of the energy field Φ and charge field Ψ within a fractal geometry of dimension D. The CP transformation corresponds to an inversion of the charge field (Ψ→−Ψ) combined with spatial reflection.

During transitions, a resonance acquires a phase factor:

$$R(t) = R_0\, e^{i(\omega t + \delta)}, \tag{21}$$

Where, R(t) is the resonance amplitude, ω is the natural frequency of the resonance mode, and δ is the interaction-induced phase shift. CP symmetry would imply that under charge inversion and parity,

$$R_{particle}(t) \equiv R_0\, e^{i(\omega t + \delta)} \xrightarrow{CP} R_{antiparticle}(t) \equiv R_0\, e^{i(\omega t - \delta)}. \tag{22}$$

However, in UFQFT the fractal geometry introduces an asymmetric phase correction Δδ(D), such that

$$R_{antiparticle}(t) = R_0\, e^{i(\omega t - \delta + \Delta\delta(D))}, \tag{23}$$

where Δδ(D)≠0 generates CP violation dynamically.

5.2 Matter–antimatter imbalance as static stability differences

Beyond dynamic shifts, UFQFT attributes particle–antiparticle asymmetry to differences in fractal stability, quantified by the effective fractal dimension D. The stability of a resonance mode is expressed through the survival probability:

$$P(t) = e^{-\Gamma(D)\,t} \tag{24}$$

where Γ(D) is the decay width dependent on the fractal dimension. If a particle and its antiparticle are represented by resonance pairs with slightly different dimensions:

$$D_{particle} = D_0 - \frac{\Delta D}{2}, D_{antiparticle} = D_0 + \frac{\Delta D}{2}, \tag{25}$$

then their decay widths differ:

$$\Delta\Gamma = \Gamma(D_{antiparticle}) - \Gamma(D_{particle}) \tag{26}$$

This leads to different lifetimes and hence a static population imbalance between matter and antimatter.

5.3 A unified framework for Sakharov's conditions

Sakharov (1967) established three necessary conditions for baryogenesis: (i) baryon number violation, (ii) C and CP violation, and (i) departure from thermal equilibrium. UFQFT provides a geometric reinterpretation:

1. **Baryon number violation**
   – arises naturally from resonance transitions in which fractal modes reconfigure between quark and lepton channels.

2. **C and CP violation**
   – expressed as both (a) dynamic phase asymmetry (Δδ(D) [Eq. (23)], and (b) static stability asymmetry (ΔD) [Eq. (25)].

3. **Departure from equilibrium**
   – encoded in the fractal evolution of spacetime itself, where fluctuations in D(t) drive systems away from detailed balance.

Thus, CP violation in UFQFT is not an isolated feature but a natural dual manifestation: resonance phase asymmetry governs micro-level transitions, while fractal stability differences shape macro-level matter dominance in the universe.

6. Cosmological Implications

The resonance-based framework of UFQFT not only addresses particle-level asymmetries but also provides a natural explanation for cosmological-scale matter–antimatter imbalance and its connection to dark sectors. The interplay of fractal stability, phase-inverted resonances, and dynamic spacetime geometry offers a unified view of baryogenesis and cosmic evolution.

6.1 Matter dominance in the observable Universe

Within UFQFT, the net matter density of the Universe arises from a resonance population imbalance. The relative abundance of matter (ρ_{M}) and antimatter ($\rho_{\bar{M}}$) after freeze-out is given by:

$$\eta \equiv \frac{\rho M - \rho \bar{M}}{\rho M + \rho \bar{M}} \tag{27}$$

where η is the matter–antimatter asymmetry parameter.

In UFQFT, η originates from two contributions:

$$\eta \approx f_{dyn}(\Delta\delta(D)) + f_{stat}(\Delta D), \tag{28}$$

where $f_{dyn}(\Delta\delta(D))$ encodes dynamic CP-violating phase shifts, and $f_{\mathrm{stat}}(\Delta D)$ represents static fractal stability differences.

6.2 Antimatter annihilation and the survival of matter

Once the Universe cooled below the pair-production threshold, particle–antiparticle pairs annihilated efficiently. The survival of matter is linked to the residual asymmetry in η. The surviving matter density is estimated as:

$$\rho_{surv} \approx \eta\, \rho_{tot} \tag{29}$$

where $\rho_{tot}$is the total matter + antimatter density prior to annihilation, and ρ_{surv} is the net surviving matter density that seeds baryonic structure formation.

6.3 Possible links to dark matter and dark energy

In UFQFT, dark matter and dark energy may be understood as complementary outcomes of resonance asymmetry:

1. **Dark Matter**: Stable, phase-inverted resonances that do not annihilate completely due to non-integer fractal dimension offsets (ΔD≠0). These modes can contribute a hidden matter density:

$$\rho_{DM} \propto e^{-\alpha|\Delta D|} \tag{30}$$

where α is a model-dependent constant controlling the suppression of hidden resonances.

2. **Dark Energy**: The residual vacuum contribution of the energy field Φ, which scales with fractal dimension evolution:

$$\rho_{\Lambda}(t) \sim \Phi^2 f(D(t)) \tag{31}$$

where f(D(t) captures the time-dependent evolution of the fractal geometry, contributing to accelerated cosmic expansion.

6.4 Early-Universe fractal evolution and cosmic expansion

The cosmological scale factor a(t) can be generalized in UFQFT by including a fractal correction term. Assuming standard Friedmann dynamics with an additional fractal factor:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}[\rho_M + \rho_{DM} + \rho_{\Lambda}(D(t))] \tag{32}$$

where G is Newton’s constant, and ρ_{Λ}(D(t)) represents the fractal vacuum energy contribution.The fractal dimension evolves as:

$$D(t) = D_0 + \Delta D\, g(t), \tag{33}$$

where g(t) is a smooth function encoding the cosmic-time evolution of resonance stability. This dynamic D(t) leads naturally to deviations from perfect matter–antimatter symmetry, providing both the seeds of baryogenesis and the late-time acceleration of the Universe. In this unit, η: matter–antimatter asymmetry parameter. Δδ(D): CP-violating phase shift correction from fractal geometry. ΔD: fractal stability difference between particle and antiparticle, ρ_{tot}: total pre-annihilation density, ρ_{surv}: net surviving matter density, ρ_{DM}: dark matter density from hidden resonances, ρ_{Λ}: fractal vacuum energy contribution, a(t): cosmological scale factor, D(t): time-dependent fractal dimension of spacetime.

7. Phenomenological Predictions and Tests

The UFQFT framework yields a number of experimentally testable predictions that distinguish it from the Standard Model and its extensions. These predictions span from laboratory-scale particle physics experiments to astrophysical and cosmological observations.

7.1 Particle–antiparticle decay asymmetries

In UFQFT, the decay probability of a particle depends explicitly on the fractal dimension D. For a resonance state with lifetime τ(D), the decay rate is:

$$\Gamma(D) = \frac{1}{\tau(D)} \tag{34}$$

If a particle–antiparticle pair has slightly shifted fractal dimensions:

$$D_p = D_0 - \frac{\Delta D}{2}, D_{\bar{p}} = D_0 + \frac{\Delta D}{2} \tag{35}$$

then their decay asymmetry is given by:

$$A_{decay} = \frac{\Gamma(D_{\bar{p}}) - \Gamma(D_p)}{\Gamma(D_{\bar{p}}) + \Gamma(D_p)} \tag{36}$$

This quantity provides a direct measure of the ΔD-driven asymmetry and can, in principle, be extracted from meson oscillation experiments.

7.2 Experimental signatures in collider physics (LHC, FCC)

High-energy colliders such as the LHC and the planned FCC provide a testing ground for UFQFT predictions. In particular, CP-violating phase shifts appear in differential cross sections of particle–antiparticle scattering:

$$\frac{d\sigma}{d\Omega} = | f(\theta, D) + e^{i\Delta\delta(D)} f_{\bar{p}}(\theta, D) |^2 \tag{37}$$

Where, σ: scattering cross section, θ: scattering angle, f(θ,D): resonance scattering amplitude for the particle, $f\bar{p}$(θ,D): corresponding amplitude for the antiparticle. A nonzero Δδ(D) leads to measurable deviations in angular distributions and CP asymmetries.

7.3 Astrophysical tests: cosmic rays, CMB anomalies

On cosmological scales, UFQFT predicts residual matter–antimatter imbalance observable in astrophysical fluxes. The expected flux ratio of cosmic ray particles (Φp) to antiparticles (Φp¯) is:

$$R_{CR} = \Phi_p \Phi_{\bar{p}} \approx e^{\beta\,\Delta D} \tag{38}$$

where β encodes propagation and annihilation effects in the interstellar medium. Additionally, early-Universe resonance phase shifts (Δδ(D)) can leave imprints on the cosmic microwave background (CMB), generating multipole anomalies. These can be parameterized as deviations in the angular power spectrum:

$$C_\ell^{obs} = C_\ell^{\Lambda CDM}[1 + \epsilon(\Delta D, \Delta\delta)], \tag{39}$$

Where, C_ℓ^{obs}: observed angular power at multipole ℓ, $C_\ell^{\Lambda CDM}$: prediction from the standard, cosmological model, $\epsilon(\Delta D, \Delta\delta)$: UFQFT-induced correction term.

7.4 Numerical modeling of ΔD effects

A key test of UFQFT lies in numerical simulations of resonance dynamics within a fractal spacetime geometry. The evolution of the particle–antiparticle population difference N(t) can be written as:

$$\frac{dN}{dt} = -\Gamma(D)\, N + S(\Delta D, \Delta\delta), \tag{40}$$

Where, N(t): net particle population, Γ(D): decay rate [Eq. (34)], S(ΔD,Δδ): source term encoding CP-violating and fractal stability contributions. By fitting S(ΔD,Δδ) to collider and cosmological data, one can extract empirical constraints on ΔD and validate UFQFT predictions. In this part, Γ(D) is decay width as a function of fractal dimension, ΔD: stability difference between particle and antiparticle, Adecay: decay asymmetry, dσ/dΩ: differential scattering cross section, Δδ(D): dynamic CP-violating phase correction, R_{CR}: cosmic ray particle–antiparticle flux ratio, $C_{\ell\mathrm{obs}}$: observed CMB angular power, S(ΔD,Δδ): source term for net particle population evolution.

8. Discussion and Outlook

The Unified Fractal Quantum Field Theory (UFQFT) provides a novel geometric interpretation of the matter–antimatter asymmetry, embedding CP violation, baryogenesis, and cosmic expansion into a single resonance-based framework. In this section, we summarize the key contributions, identify theoretical limitations, and outline possible avenues for future research and testing.

8.1 Summary of UFQFT contributions to the matter–antimatter problem

UFQFT explains matter–antimatter asymmetry as a dual manifestation of:

1. **Dynamic resonance phase shifts** (Δδ(D) → generating CP violation during particle transitions.
2. **Static stability asymmetries** (ΔD → producing long-term population imbalances between particles and antiparticles.

The baryon asymmetry parameter, central to cosmology, is thus expressed as:

$$\eta_{UFQFT} = f_{dyn}(\Delta\delta(D)) + f_{stat}(\Delta D) \tag{41}$$

where $f_{dyn}$and f_{stat} are functional contributions from dynamical and static mechanisms, respectively.

8.2 Open challenges and theoretical limitations

While UFQFT offers a unified perspective, several challenges remain:

- **Quantitative calibration**: The explicit functional form of f_{dyn} and f_{stat} [Eq. (41)] must be derived from first-principles within fractal field dynamics, rather than phenomenological modeling.
- **Consistency with QFT**: Embedding UFQFT within the renormalization framework of quantum field theory requires a generalized treatment of propagators in fractal geometries.

- **Experimental resolution**: Current data on CP violation (e.g., kaon and B-meson decays) constrain phase shifts but cannot yet directly probe small deviations in D.

Thus, while the framework is conceptually robust, further development is necessary for precision predictive power.

8.3 Future directions: phenomenology, astrophysics, high-energy experiments

UFQFT can be tested through multiple pathways:

1. **Collider Phenomenology**:
   - Differential cross-section asymmetries [Eq. (37)] provide direct probes of Δδ(D).
   - Heavy-flavor meson factories (Belle II, LHCb) may constrain ΔD via decay asymmetries [Eq. (36)].
2. **Astrophysical Observations**:
   - Cosmic ray particle–antiparticle flux ratios [Eq. (38)] offer indirect probes of large-scale ΔD.
   - CMB multipole anomalies [Eq. (39)] may encode early-Universe resonance asymmetries.
3. **Numerical Simulations**:
   - Time-evolution of population imbalance governed by [Eq. (40)] can be simulated under varying ΔD and Δδ(D)).
   - Comparison with cosmological baryon-to-photon ratio ($\eta_{obs} \approx 6 \times 10^{-10}$) offers an immediate test.

8.4 Toward a unified explanation of baryogenesis and cosmic acceleration

Perhaps the most far-reaching contribution of UFQFT is the suggestion that baryogenesis and cosmic acceleration are two outcomes of the same fractal mechanism. If the fractal dimension evolves dynamically as:

$$D(t) = D_0 + \varDelta D\, g(t), \tag{42}$$

then:

- **Early-time deviations** ($t \ll t_0$) produce matter–antimatter asymmetry through ΔD induced stability differences.
- **Late-time evolution** ($t \sim t_0$) yields an effective vacuum contribution:

$$\rho_\varLambda(t) \sim \varPhi^2 f(D(t)), \tag{43}$$

which drives cosmic acceleration. Thus, baryogenesis and dark energy are not unrelated phenomena but two temporal faces of the same fractal resonance dynamics.in this part, η_{UFQFT} matter–antimatter asymmetry parameter predicted by UFQFT, f_{dyn}(Δδ(D)) dynamic CP-violating contribution, f_{stat}(ΔD): static stability contribution, D(t): time-dependent fractal dimension of spacetime, ρ_Λ(t): fractal vacuum energy density.

9. Conclusion

In this work, we have developed a comprehensive framework for interpreting matter–antimatter asymmetry within the Unified Fractal Quantum Field Theory (UFQFT). By embedding particle definitions into fractal spacetime geometry, the model naturally explains the emergence of asymmetric resonance stabilities as the origin of baryogenesis. Matter and antimatter were treated as π-shifted resonance modes of the same underlying fields—the energy field (Φ) and the charge field (Ψ)—where differences in fractal dimension ΔD act as the source of CP violation and decay asymmetries. The analysis has shown that UFQFT provides a geometric foundation for Sakharov's conditions, unifying CP violation, matter–antimatter imbalance, and baryon number non-conservation under a single resonance-based principle. Unlike the Standard Model, where CP violation arises from parameterized mixing matrices, UFQFT attributes this asymmetry to structural properties of fractal spacetime, making it inherently geometric and scale-dependent. From a cosmological perspective, the framework connects baryogenesis to early-Universe fractal evolution, linking the suppression of antimatter domains to the observed matter dominance. Moreover, potential connections to dark matter and dark energy suggest that the same resonance asymmetry mechanism could underlie both microscopic and macroscopic phenomena. Phenomenological predictions—including particle–antiparticle decay asymmetries, collider observables, and astrophysical signatures—highlight pathways for testing this model. If validated, UFQFT could provide a unified explanation of baryogenesis, CP violation, and cosmic acceleration, pointing toward a more complete understanding of the Universe's matter content and its large-scale dynamics.

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