

Unified Field Theory Based on Quantum Phase Structure of Spacetime: A New Approach to the Theory of Everything

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Abstract

This paper proposes a new unified field theory based on the quantum phase structure of spacetime. This theory not only describes the four fundamental interactions of nature (gravity, electromagnetism, strong force, and weak force) as geometric and topological properties of spacetime in a unified manner, but also provides a coherent interpretation for dark matter and dark energy. In particular, we present an innovative perspective that interprets the parity symmetry breaking of the weak interaction as a distortion of spacetime involving the time direction, suggesting that "the weak force is the only force dependent on the direction of time." Furthermore, we introduce the concept of "phase defect black holes (topological solitons)" as an alternative to black holes, demonstrating a natural resolution to the information paradox. We also discuss in detail the specific predictions from the theory and their experimental verifiability.

Keywords: Unified field theory, Quantum phase geometry, Topological soliton, Weak interaction, Parity symmetry breaking, Dark matter, Dark energy

1. Introduction

1.1 Background

Despite its many successes, modern physics faces several fundamental mysteries. These include the unified understanding of the four fundamental interactions of nature (gravity, electromagnetism, strong force, and weak force), the black hole information paradox, and the nature of dark matter and dark energy. While the Standard Model and general relativity boast high precision in their respective domains, a complete "Theory of Everything" that integrates these has yet to be established.

Recently, Lindgren et al. [1] proposed a groundbreaking framework reinterpreting electromagnetism as a purely geometric theory. Simultaneously, Heidmann et al. [2] introduced the concept of "phase defect black holes (topological solitons)" as an alternative to black holes, characterizing them as smooth spacetime structures without event horizons or singularities.

1.2 Objectives of This Research

The purpose of this research is to integrate and develop the approaches of Lindgren [1] and Heidmann [2] to construct a comprehensive unified field theory based on the quantum phase structure of spacetime. Specifically, we focus on:

1. Establishing a mathematical framework that describes the four fundamental interactions as geometric and topological properties of spacetime in a unified manner
2. Proposing a new perspective that interprets the parity symmetry breaking of the weak interaction as a distortion of spacetime involving the time direction
3. Deriving a unified understanding of dark matter and dark energy naturally from the quantum phase structure of spacetime
4. Discussing the experimental verifiability and specific predictions of the proposed theory

1.3 Theoretical Framework

The theoretical framework proposed in this paper is based on the following fundamental assumptions:

1. Spacetime is not merely a background but a dynamic phase geometric structure with quantum properties
2. Fundamental interactions are manifestations of different aspects of this quantum phase structure
3. Matter fields are inseparably linked to the spacetime structure
4. Topological invariants underlie the fundamental laws of physics

2. Geometric Representation of the Strong Interaction

2.1 Fiber Bundle Structure of Non-Abelian Gauge Fields

For the geometric representation of the strong interaction, we employ fiber bundle theory. The basic structure is formulated as follows:

- Base manifold M : 4-dimensional spacetime
- Fiber F : SU(3) group
- Total space E : SU(3) principal bundle over M
- Connection ω : corresponding to the Yang-Mills field

In this mathematical framework, the gluon field G_μ^a is interpreted as a component of the connection on the principal bundle, expressed as:

$$G_\mu^a = \langle \omega_\mu, T^a \rangle$$

where T^a are the generators of the SU(3) Lie algebra, and the curvature of the connection is:

$$F_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + f^{abc} G_\mu^b G_\nu^c$$

This curvature corresponds to the gluon field strength tensor.

2.2 Extended Metric Tensor

We define an extended metric tensor that includes the strong interaction as follows:

$$g_{\mu\nu} = \eta_{\mu\nu} + \kappa_E A_\mu A_\nu + \kappa_S \sum_{a=1}^8 G_\mu^a G_\nu^a$$

where κ_E and κ_S are parameters representing the geometric "coupling strengths" of the electromagnetic and strong interactions, respectively. From dimensional analysis, these can be set as:

$$\kappa_E = \frac{e^2}{M_P^2}, \quad \kappa_S = \frac{g_s^2}{M_P^2}$$

where M_P is the Planck mass, e is the charge, and g_s is the strong coupling constant.

2.3 Topological Interpretation of Color Confinement

To interpret color confinement (the phenomenon where quarks are not observed in isolation) geometrically, we introduce a topological invariant:

$$\mathcal{C} = \int_V \epsilon^{\mu\nu\rho\sigma} \text{Tr}(F_{\mu\nu} F_{\rho\sigma}) d^4x$$

This quantity is related to the topology of spacetime and can be interpreted as giving rise to color confinement when it takes non-trivial values. This corresponds mathematically to solutions known as "instantons."

2.4 Geometric Interpretation of Asymptotic Freedom

The characteristic of QCD known as asymptotic freedom (the decrease in coupling constant at high energies) can also be interpreted geometrically. Considering the scale dependence of the extended metric:

$$g_{\mu\nu}(Q^2) = \eta_{\mu\nu} + \kappa_E A_\mu A_\nu + \kappa_S(Q^2) \sum_{a=1}^8 G_\mu^a G_\nu^a$$

The scale dependence of $\kappa_S(Q^2)$ is given by:

$$\kappa_S(Q^2) = \frac{g_s^2(Q^2)}{M_P^2} = \frac{g_s^2(Q_0^2)}{M_P^2} \frac{1}{1 + \frac{33-2n_f}{12\pi} \ln(Q^2/Q_0^2)}$$

where n_f is the number of quark flavors. This indicates that the geometric structure of spacetime itself changes with distance scale, with the effects of the strong interaction geometrically "diluting" at short distances.

3. Consistency of Quantum Effects and Geometric Representation of Spacetime

3.1 Geometric Representation of Quantum Fields

Matter fields (quarks and leptons) can be represented as spinor fields on the extended spacetime manifold:

$$\mathcal{L}_{\text{Dirac}} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi$$

where D_μ is the extended covariant derivative, defined as:

$$D_\mu = \partial_\mu + \frac{1}{4}\omega_{\mu ab}\gamma^a\gamma^b - ieA_\mu - ig_s G_\mu^a t^a$$

Here, $\omega_{\mu ab}$ is the spin connection, γ^a are the Dirac gamma matrices, and t^a are the SU(3) generators.

Importantly, this covariant derivative unifies the treatment of spacetime geometry and internal symmetry (gauge symmetry).

3.2 Topological Interpretation of Quantum Effects

Quantum effects, particularly anomalies, can be interpreted from a topological perspective. For example, the chiral anomaly is:

$$\partial_\mu j^{\mu 5} = \frac{e^2}{16\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{g_s^2}{16\pi^2} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$

where $\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$.

This equation is related to the Atiyah-Singer index theorem and shows that quantum effects are directly linked to the topological characteristics of spacetime. In our unified theory, this anomaly naturally arises from quantum fluctuations of the metric.

3.3 Geometric Path Integral

To incorporate quantum effects, we consider the path integral of the metric tensor:

$$Z = \int \mathcal{D}g_{\mu\nu} \mathcal{D}\psi \mathcal{D}\bar{\psi} e^{iS[g_{\mu\nu}, \psi, \bar{\psi}]}$$

where S is the total action. The quantum fluctuations of the metric represent the quantum properties of the phase space.

4. Relationship Between Parity Symmetry Breaking and Time Direction

4.1 Chiral Structure of Spacetime

We introduce a geometric framework with an inherently chiral (left-right asymmetric) structure by extending the normal spacetime manifold:

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu + \epsilon_{\mu\nu\rho\sigma} W^\mu dx^\nu dx^\rho dx^\sigma$$

where the second term is the chiral contribution, and W^μ is related to the weak interaction potential. This chiral term has particularly important contributions in the time direction ($\mu = 0$) and changes sign under the parity transformation $\vec{x} \rightarrow -\vec{x}$.

4.2 Extended Connection and Torsion

The connection corresponding to this extended metric includes, in addition to the standard Christoffel symbols, a chiral term:

$$\Gamma_{\mu\nu}^\lambda = \left\{ \begin{matrix} \lambda \\ \mu\nu \end{matrix} \right\} + T_{\mu\nu}^\lambda$$

The chiral term $T^{\lambda}_{\mu\nu}$ is defined as:

$$T^{\lambda}_{\mu\nu} = g^{\lambda\sigma} \epsilon_{\sigma\mu\nu\rho} W^{\rho}$$

Unlike the usual torsion-free connection, this connection has torsion (twist):

$$T^{\lambda}_{\mu\nu} - T^{\lambda}_{\nu\mu} \neq 0$$

This torsion is directly related to parity symmetry breaking.

4.3 Predominance of Time Direction

We mathematically formulate the reason why only the weak interaction has a special relationship with the time direction. We assume that the time component W^0 of the weak interaction potential W^{μ} has an essentially different coupling compared to the spatial components:

$$W^{\mu} = (W^0, \vec{W}) = (W^0, \chi \vec{W})$$

where χ is the parity non-conservation parameter. Parity is conserved when $\chi = 1$ and violated when $\chi \neq 1$. In nature, $\chi \approx 0$ has been measured.

4.4 Macroscopic Direction of Time

We consider the relationship between parity non-conservation in the weak interaction and the arrow of time (the unidirectionality of time). With the presence of torsion terms, the geodesic equation becomes asymmetric with respect to time reversal:

$$\frac{d^2 x^{\mu}}{d\tau^2} + \Gamma^{\mu}_{\nu\lambda} \frac{dx^{\nu}}{d\tau} \frac{dx^{\lambda}}{d\tau} \neq \frac{d^2 x^{\mu}}{d(-\tau)^2} + \Gamma^{\mu}_{\nu\lambda} \frac{dx^{\nu}}{d(-\tau)} \frac{dx^{\lambda}}{d(-\tau)}$$

This asymmetry may be the origin of the macroscopic directionality of time.

5. Interpretation of Dark Matter and Dark Energy through Spacetime Phase Structure

5.1 Dark Matter as Topological Defects

We propose a theoretical framework that interprets dark matter as topological defects in spacetime. Specifically, we consider that non-trivial topological structures in higher-dimensional spacetime (five dimensions or more), when projected onto four-dimensional spacetime, appear as "topological defects" with interaction properties different from ordinary matter:

$$\rho_{DM}(x) = \int_{\mathcal{M}_5} \sqrt{-g_5} \mathcal{T}(X) \delta^{(4)}(x - X) d^5 X$$

where \mathcal{M}_5 is a 5-dimensional manifold, $\mathcal{T}(X)$ is a topological invariant, and g_5 is the 5-dimensional metric.

5.2 Vacuum Energy of Quantum Phase Space

We interpret dark energy as an essential characteristic of the quantum phase structure of spacetime. The vacuum energy density of quantum phase space is:

$$\rho_{\Lambda} = \frac{\hbar}{l_P^4} \sum_{\text{topologies}} e^{-S_E[\text{topology}]}$$

where l_P is the Planck length and S_E is the Euclidean action. This sum is over all possible topologies, and the contribution of non-trivial topologies becomes the cause of the accelerated expansion of the universe.

5.3 Unification of Dark Matter and Dark Energy

In our theory, dark matter and dark energy can be understood as different aspects of the same phenomenon. The relationship between them is:

$$\rho_{DE} = \frac{\hbar}{M_P^2} \nabla_{\mu} \nabla^{\mu} \rho_{DM}$$

This relationship indicates that dark energy arises from the density gradient of dark matter.

6. Phase Defect Black Holes and the Information Paradox

6.1 Mathematical Description of Topological Solitons

Phase defect black holes can be represented as special topological soliton solutions:

$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2 d\Omega^2 + h(r)(dy + A_{\mu} dx^{\mu})^2$$

where y is an extra dimension, A_{μ} is the gauge potential, and $f(r)$ and $h(r)$ are radial functions.

6.2 Information Preservation Mechanism

In phase defect black holes, there is no event horizon and no singularity in the interior. This resolves the fundamental problem of information being completely lost. Information is preserved in the internal structure (topology) of the phase defect and is, in principle, recoverable.

In quantum phase space, information is encoded in the topological structure itself. This is represented not as bit sequences in normal space but as topological characteristics (e.g., homotopy groups and cohomology classes). Even if information appears to "disappear" locally, it is preserved in the global topological structure.

7. Experimental Verifiability

7.1 Verification in Particle Physics Experiments

Our unified theory makes the following predictions in high-energy particle physics experiments:

$$\sigma(pp \rightarrow X) = \sigma_{SM}(pp \rightarrow X) \times \left[1 + \delta_T \left(\frac{E}{M_T} \right)^2 \right]$$

where σ_{SM} is the Standard Model prediction, ΔT is the topological correction, and M_T is the topological scale.

7.2 Precision Gravitational Wave Observations

In gravitational wave observations, topological effects appear in the following forms:

- Phase Shift:** $\Psi_{GW}(f) = \Psi_{GR}(f) + 2\pi f \Delta t_T + \beta_T f^2$ where Δt_T is the propagation time correction and β_T is the topological dispersion parameter.
- Echo Signal:** Characteristic echo patterns should be detected from phase defect black holes:
 $h_{echo}(t) = \alpha_{echo} \cdot h_{main}(t - \Delta t_{echo}) \cdot e^{-t/\tau_T}$ where α_{echo} is the echo intensity, Δt_{echo} is the echo time interval, and τ_T is the topological decay time.

7.3 Astrophysical Observations

- Black Hole Imaging with the Event Horizon Telescope (EHT):** The next-generation upgrade of the EHT can search for evidence of phase defect black holes by observing the internal structure of the black hole "shadow" in more detail.
- Galaxy Rotation Curves:** The anomalies in galaxy rotation curves can be explained by specific distributions of topological defects. The mass density distribution of topological defects within galaxies is: $\rho_{DM}(r) = \frac{\rho_0}{1+(r/r_s)^2}$ This distribution matches the observed rotation curves and serves as an alternative to the NFW profile.

8. Conclusion and Outlook

The unified field theory based on the quantum phase structure of spacetime provides a new framework for understanding the four fundamental interactions of nature, dark matter, and dark energy in a unified manner. This theory integrates and develops the research of Lindgren et al. [1] on the purely geometric description of electromagnetism and the research of Heidmann et al. [2] on phase defect black holes.

The greatest strength of this theory is the possibility of explaining a wide range of phenomena from particle physics to cosmology from the single concept of topological spacetime structure. It is expected that future experimental verification and theoretical development will bring us one step closer to completing the "Theory of Everything."

In particular, the perspective that the weak interaction is "the only force dependent on the direction of time" may shed new light on the origin of the unidirectionality of time, a fundamental mystery in physics. If this perspective is correct, the fundamental laws of nature are based not only on spatial symmetry but also on the essential asymmetry of time and space.

Our theory proposes bold answers to the most profound mysteries of modern physics, but its validity should ultimately be judged by experimental verification. We hope that the day will come when the predictions of this theory are verified through next-generation high-energy physics experiments, precision gravitational wave observations, and cosmological observations.

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