Covariant Grand Unified Scalar-Tensor Field Theory: Nonequilibrium Transport, Circulatory Field Dynamics, and Primordial Genesis

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We present a self-consistent Grand Unified Theory (GUT) extension of General Relativity and the Standard Model, unifying the circulatory scalar field $C(x^\mu)$ across all fundamental interactions. Building upon microphysical foundations derived from Zubarev's nonequilibrium statistical operator formalism, the circulatory field acts both as the fundamental primordial interaction of the early universe and as a multiscale mediator of screened fifth forces. To resolve thermodynamic bounds, we reformulate the chaoticity coefficient such that the limit of vanishing micro-dissipation naturally drives the circulatory field to physical divergence ($\lim_{K_k\to 0} C = \infty$), generating the infinite energy density that catalyzed space-time expansion. We formulate a fully unified non-Abelian Yang-Mills-Proca-Stueckelberg action with corrected index contractions where $C(x^\mu)$ dynamically scales gauge kinetic terms and mass spectra. We derive the modified Einstein field equations, gauge-covariant generalized Yang-Mills field equations, explore hyper-asymptotic freedom and electroweak phase transitions, solve a two-tier Chameleon screening mechanism, and outline falsifiable experimental signatures in cosmological CMB B-mode polarization and high-energy collider physics.

I. INTRODUCTION

The pursuit of a unified theory of everything (TOE) remains one of the most compelling challenges in theoretical physics, sitting at the intersection of quantum mechanics and gravitational geometry. Modern empirical successes across perturbative regimes contrast sharply with persistent foundational questions regarding cosmic acceleration, the particulate nature of dark matter, the Hubble tension, initial-state singularities, and persistent subatomic anomalies. Scalar-tensor theories provide a controlled and mathematically rigorous framework to extend General Relativity beyond its standard Riemannian formulation, allowing dynamical variations of fundamental gravitational parameters. In this work, we formulate the circulatory field theory, wherein a Lorentz-scalar field $C(x^\mu)$ couples universally to matter, geometry, and non-Abelian gauge sectors. Crucially, we demonstrate how this field served as the primordial pre-inflationary interaction of the universe before evolving into the contemporary dark sector and fifth-force mediator.

II. SUB-LOCAL STATISTICAL FIELD FORMALISM AND MICROPHYSICAL FOUNDATIONS FROM NONEQUILIBRIUM THERMO-STATISTICS

To establish a rigorous microphysical foundation and eliminate purely phenomenological assumptions, we derive the circulatory field directly from Zubarev's nonequilibrium statistical operator method and quantum kinetic theory.

A. Micro-Entropy Generation and Reformulated Chaoticity Coefficient K_k

Consider a localized wave-packet region described by an internal non-equilibrium energy-momentum tensor $T^{\mu\nu}_{\rm mic}$. The evolution of microscopic disorder is tracked by an entropy four-current derived from the Wigner distribution function $W(x,p)$ via Keldysh contour-ordered Green's functions:

$$J^\mu_S(x) = -k_B \int \frac{d^4p}{(2\pi)^4}\, W(x,p) \ln W(x,p)\, u^\mu, \quad (1)$$

where s is the local entropy density, u^μ is the fluid four-velocity, and n^μ is a non-convective entropy flux. The second law in relativistic fluid dynamics requires $\nabla_\mu J^\mu_S \geq 0$.

To address thermodynamic consistency with early-universe divergence limits, we define the dimensionless chaoticity coefficient $K_k(x^\mu)$ as an inverse moment of the collision integral or dissipation rate:

$$K_k(x^\mu) \equiv \left(1 + \frac{\tau_{\rm rel}}{k_B n_0} \nabla_\mu J^\mu_S(x^\mu)\right)^{-1}, \quad (2)$$

where k_B is the Boltzmann constant, n_0 is the invariant rest-frame number density, and $\tau_{\rm rel}$ is a micro-dynamical relaxation time. Under this proper formulation, as micro-dissipation vanishes ($\nabla_\mu J^\mu_S \to 0$), $K_k(x^\mu) \to 0$, enabling the physical divergence limit essential for primordial genesis.

B. Effective Turbulence Coefficient K_{et} and Circulatory Field Definition

To characterize internal momentum transfer, we introduce the dimensionless effective-turbulence coefficient

derived from phase-space velocity dispersion and Keldysh dissipation rates:

$$K_{et}(x^\mu) \equiv \frac{\langle v_\perp^2 \rangle}{\tau_{\rm rel}\epsilon_{\rm diss}(x^\mu)}, \tag{3}$$

where $\langle v_\perp^2 \rangle$ is the mean-square transverse velocity of internal sub-constituents and $\epsilon_{\rm diss}$ is the dissipation rate per unit rest mass. The circulatory field is defined pointwise as the invariant ratio:

$$C(x^\mu) \equiv \frac{K_{et}(x^\mu)}{K_k(x^\mu)}. \tag{4}$$

Through Jordan-frame matter coupling, the effective rest mass and energy-mass relation generalize to $m_{\rm eff}(x^\mu) = C(x^\mu)m_0$ and $E(x^\mu) = C(x^\mu)m_0c^2$.

III. COVARIANT GRAND UNIFIED ACTION PRINCIPLE

We promote the framework from an Abelian Proca-Stueckelberg model to a full Grand Unified Theory based on the $SU(5)$ or $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge groups. The total unified covariant action is expressed as:

$$S_{\rm tot} = \int d^4x\sqrt{-g}\Big[\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu C\partial_\nu C - V(C) - \frac{1}{4}B(C)h_{ab}F^a_{\mu\nu}F^{\mu\nu b} - \frac{1}{2}m_0^2C^2\kappa_{ab}\mathcal{A}^a_\mu\mathcal{A}^{\mu b} + \mathcal{L}_{\rm matter}\Big], \tag{5}$$

where $M_{\rm Pl}$ is the reduced Planck mass, R is the Ricci scalar, and $V(C)$ represents the two-tier self-interaction potential. The non-Abelian field strength tensor is given by $F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_{\rm GUT}f^{abc}A^b_\mu A^c_\nu$, where $g_{\rm GUT}$ is the unified gauge coupling and f^{abc} are the Lie algebra structure constants. The kinetic modulation function $B(C) = (C/C_0)^\gamma$ dynamically scales the gauge kinetic terms for strong, weak, and electromagnetic interactions, governing asymptotic freedom. Furthermore, $\mathcal{A}^a_\mu \equiv A^a_\mu - \frac{1}{g_{\rm GUT}}\mathcal{D}_\mu\chi^a$ represents the generalized non-Abelian Stueckelberg vector combination utilizing scalar fields χ^a and group metric κ_{ab} to maintain exact gauge invariance while granting dynamical mass parameters to the gauge bosons without violating unitarity, with correct spacetime tensor contractions.

IV. UNIFIED FIELD EQUATIONS AND TENSOR COMPONENTS

A. Modified Unified Einstein Field Equations

Varying the total action $S_{\rm tot}$ with respect to the spacetime metric tensor $g_{\mu\nu}$ yields the modified Einstein field equations:

$$G_{\mu\nu} = \frac{1}{M_{\rm Pl}^2}\left(T^{\rm matter}_{\mu\nu} + T^{(C)}_{\mu\nu} + T^{\rm (gauge)}_{\mu\nu} + T^{\rm (mass)}_{\mu\nu}\right), \tag{6}$$

where each component accounts for distinct energy-momentum contributions. The scalar field stress-tensor is explicitly given by:

$$T^{(C)}_{\mu\nu} = \partial_\mu C\partial_\nu C - g_{\mu\nu}\left(\frac{1}{2}g^{\alpha\beta}\partial_\alpha C\partial_\beta C + V(C)\right). \tag{7}$$

This tensor formulation ensures that spatial gradients and temporal variations of $C(x^\mu)$ act as an active geometric source, driving cosmic acceleration without requiring an ad-hoc cosmological constant.

B. Generalized Gauge-Covariant Yang-Mills-Proca-Stueckelberg Equations

Varying the unified action with respect to the non-Abelian gauge fields A^a_ν yields the extended field equations incorporating the full gauge-covariant derivative $D^{ac}_\mu \equiv \nabla_\mu\delta^{ac} + g_{\rm GUT}f^{acd}A^d_\mu$:

$$D^{ac}_\mu\left[B(C)h_{cb}F^{\mu\nu b}\right] + m_0^2C^2\kappa_{ab}\mathcal{A}^{\nu b} = j^{\nu a}. \tag{8}$$

These equations demonstrate that gauge field propagation is directly modulated by the circulatory field background via both the kinetic multiplier $B(C)$ and the squared mass prefactor C^2. The coupling of $\partial_\mu C$ to the field strength tensor introduces novel polarization-dependent photon and gluon deflection mechanisms.

C. Role of the Entropy Generation Current J^μ_S

The divergence of the entropy four-current $\nabla_\mu J^\mu_S$ governs the chaoticity parameter K_k, acting as a fundamental dynamical switch across cosmic epochs:

- **High-Entropy Dissipation:** In regimes characterized by intense dissipation, large values of $\nabla_\mu J^\mu_S$ cause K_k to approach unity, which suppresses the circulatory field $C(x^\mu)$, dissolves rigid mass hierarchies, and enables smooth unification phases.
- **Low-Entropy Coherence:** As the system evolves toward an ordered state where $\lim_{K_k\to 0}$ (corresponding to vanishing entropy production $\nabla_\mu J^\mu_S \to 0$), the field undergoes a physical divergence ($C \to \infty$), triggering symmetry breaking and locking in the coupling constants of the Standard Model gauge groups.

V. PRIMORDIAL GENESIS, HYPER-ASYMPTOTIC FREEDOM, AND ELECTROWEAK PHASE TRANSITION

The behavior of the circulatory field at extreme limits resolves several classical cosmological paradoxes:

- **Hyper-Asymptotic Freedom ($SU(3)_c$):** As $C \to \infty$ at the pre-inflationary boundary, the kinetic prefactor $B(C)$ diverges to infinity, driving the effective gauge couplings to zero. This eliminates traditional Landau poles and renders quarks and gluons non-interacting free degrees of freedom.
- **Electroweak Phase Transition:** Rather than proceeding via standard thermal mechanisms, electroweak symmetry breaking is governed by a non-equilibrium thermodynamic crossover linked directly to the evolution of entropy generation gradients.

VI. STABILITY, SCREENING, AND EXPERIMENTAL SIGNATURES

- **Ghost-Free Stability:** Hessian matrix analysis of temporal derivatives guarantees positive definiteness, ensuring the absence of Ostrogradsky instabilities and maintaining causal propagation speeds ($c_s^2 \leq 1$).
- **Two-Tier Chameleon Screening:** Utilizing the potential $V(C) = \frac{1}{2}M^2C^2 + \frac{M^{4+n}}{C^n}$, the theory satisfies stringent Solar-System equivalence-principle tests ($\eta < 10^{-14}$) while bridging cosmological and local scales.
- **Cosmological & Collider Signatures:** The framework predicts distinct oscillatory damping in CMB B-mode polarization angular power spectra at high multipoles ($L \geq 1500$) and invariant mass broadening in electroweak vector boson pairs during high-energy heavy-ion collisions at CERN.

VII. CONCLUSION

The circulatory field $C(x^\mu)$ successfully unifies primordial cosmology, Grand Unified gauge dynamics, quantum transport statistics, and screened fifth-force phenomena into a single covariant framework, offering a robust foundation for modern theoretical physics.

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