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The Strong Coupling Constant α_s: Standard QCD, Running, and a Vacuum-Hydrodynamic Hypothesis for Its Origin and Relation to *G*

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Abstract

The strong coupling constant α_s is a fundamental parameter of quantum chromodynamics (QCD), governing the interaction strength between quarks and gluons and the transition between asymptotic freedom and confinement. In standard QCD, α_s is defined as the renormalized SU(3) gauge coupling, fixed at a reference scale and evolved through the renormalization group. The current Particle Data Group benchmark value is $\alpha_s(m_Z) = 0.1180 \pm 0.0009$, where m_Z denotes the *Z*-boson mass scale. This value is an experimentally calibrated normalization of a running coupling, not a number derived from more fundamental constants within orthodox QCD. This work examines a non-standard vacuum-based framework in which the physical vacuum is modeled as a structured medium and elementary particles are treated as vortex-like configurations. The central claim is that the effective drag coefficient C_D is not obtained from QCD and is not fitted from α_s. Rather, C_D is first derived from a hydrodynamic vacuum-resistance relation. Using the vacuum-density scale $\rho_{\text{vac}} = 9.51 \times 10^{-27}\ \text{kg} \cdot \text{m}^{-3}$ and a pressure-normalized gravitational vacuum-resistance scale $P_G = 6.67430 \times 10^{-11}\ \text{N} \cdot \text{m}^{-2}$, the model gives $C_D = \dfrac{2P_G}{\rho_{\text{vac}} c^2} = 0.15618 \simeq 0.156.$. Only after this hydrodynamic coefficient has been obtained is it compared with the QCD color-weighted benchmark coupling. The correspondence $C_D \simeq \dfrac{4}{3}\alpha_s(m_Z)$ then implies $\alpha_s^{\text{model}}(m_Z) \simeq \dfrac{3}{4} C_D = 0.11713,$ which lies close to the PDG benchmark value. Conversely, using $\alpha_s(m_Z) = 0.1180$ gives $\rho_{\text{vac}} = 9.44 \times 10^{-27}\ \text{kg} \cdot \text{m}^{-3}$, differing by less than one percent from the assumed vacuum-density scale. These results do not constitute a derivation within standard QCD. They define a testable hypothesis in which confinement and gravitation are interpreted as different regimes of a common structured-vacuum dynamics. The main significance of the approach is to reinterpret the strong coupling benchmark as the color-channel projection of an independently obtained vacuum-resistance coefficient, while clearly identifying the theoretical requirements needed for the model to become a complete physical theory: dimensional derivation of the G-to-pressure mapping, derivation of the QCD running behavior, and quantitative comparison with lattice QCD observables.

Keywords

Strong Coupling Constant, Quantum Chromodynamics, Asymptotic Freedom, Gravitational Constant, Vacuum Drag, Vortex Model, Dimensional Transmutation, Confinement

1. Introduction

The strong interaction is the fundamental force responsible for binding quarks into hadrons and for stabilizing atomic nuclei through the residual strong force. Its modern description is quantum chromodynamics, a non-Abelian gauge theory based on the color group SU(3). One of the major conceptual achievements of twentieth-century physics was the discovery that this theory is asymptotically free: the interaction becomes weaker at shorter distances and higher energies [1] [2].

In modern practice, the strength of the interaction is encoded in the strong coupling constant α_s. Yet the word "constant" is potentially misleading. Unlike the exact speed of light in vacuum, α_s depends on the renormalization scale. The commonly quoted value near 0.118 is not the value of the strong interaction at all distances and is not a low-energy constant inside every hadron. It is the reference value of the running coupling at the Z-boson mass scale, chosen because this is a clean and widely used high-energy benchmark [3]-[5].

This distinction leads to two different questions. The first is the standard QCD question: how is α_s defined, measured, and evolved with scale? The second is an interpretive question: why does the benchmark value lie near 0.118, and can that number be related to a deeper physical mechanism? The present paper addresses both questions while keeping established QCD clearly separate from the proposed non-standard vacuum-hydrodynamic interpretation.

2. Standard Meaning of α_s in QCD

In standard QCD, the strong coupling is defined from the renormalized SU(3) gauge coupling g_s by

$$\alpha_s(\mu) = \frac{g_s^2(\mu)}{4\pi}. \tag{1}$$

Here μ is the renormalization scale. The numerical value of α_s at a chosen scale is not predicted *ab initio* by perturbative QCD. Instead, it is determined at a reference scale from experimental data and lattice QCD, and then evolved to other scales through the renormalization group [3]-[5].

At one loop, using the conventional derivative with respect to μ, the running is governed by

$$\mu \frac{\mathrm{d}\alpha_s}{\mathrm{d}\mu} = -\frac{\beta_0}{2\pi}\alpha_s^2 + O\left(\alpha_s^3\right), \quad \beta_0 = 11 - \frac{2}{3}n_f, \tag{2}$$

where n_f is the number of active quark flavors. The corresponding one-loop solution may be written as

$$\alpha_s(Q) = \frac{4\pi}{\beta_0 \ln\left(Q^2/\Lambda_{\mathrm{QCD}}^2\right)}. \tag{3}$$

Equation (3) summarizes two central features of QCD. At large momentum transfer Q, the logarithm is large and α_s becomes small, allowing perturbation theory and the partonic description of quarks and gluons. At low Q, α_s becomes large and the theory enters the non-perturbative confinement regime. The QCD scale Λ_{QCD} is not inserted as a classical mass parameter; it emerges through dimensional transmutation once the coupling is renormalized [3]-[9].

The current PDG 2025 online QCD review quotes the world average

$$\alpha_s(m_Z) = 0.1180 \pm 0.0009. \tag{4}$$

This value should be understood as a reference normalization of a running coupling. Determinations from hadronic τ decays, deep-inelastic scattering, event-shape observables, electroweak precision fits, collider data, quarkonium physics, and lattice QCD are compared after being evolved to a common reference scale [3]-[5].

3. The Role of Λ_{QCD} and Dimensional Transmutation

The QCD scale Λ_{QCD} plays a crucial role in standard theory. It is the scale generated when a dimensionless coupling is renormalized and traded for a dimensional scale. In perturbative QCD, Λ_{QCD} is the integration constant that fixes the running curve of α_s. In physical terms, it marks the transition from short-distance perturbative behavior to long-distance non-perturbative confinement.

The hydrodynamic vacuum model does not replace the standard definition of Λ_{QCD}. Rather, if the model is to become a genuine physical theory, it must reinterpret this scale as a vacuum-vortex coherence scale. A natural hypothesis is that Λ_{QCD} corresponds to the inverse coherence length of the structured vacuum around color-vortex configurations:

$$\ell_{\mathrm{QCD}} \sim \frac{\hbar c}{\Lambda_{\mathrm{QCD}}}. \tag{5}$$

In this reading, ℓ_{QCD} represents the characteristic length at which vacuum resistance becomes coherent and non-perturbative. Above this scale in energy, or below this scale in distance, the probe resolves only weakly coupled local disturbances. Below this scale in energy, or above this scale in distance, the extended vacuum-vortex deformation becomes coherent and confinement emerges. This interpretation remains hypothetical. A successful theory must derive Λ_{QCD} from vacuum density, vortex geometry, and boundary conditions rather than inserting it as an empirical parameter.

4. Relation of α_s to Other Dimensionless Constants

The strong coupling belongs to a broader family of dimensionless coupling constants. The best-known comparison is the electromagnetic fine-structure constant,

$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} \simeq \frac{1}{137.036}. \tag{6}$$

Both α and α_s are dimensionless and both run with energy scale, but their physical meanings differ. The electromagnetic coupling belongs to an Abelian U(1) gauge theory, while α_s belongs to a non-Abelian SU(3) gauge theory. The self-interaction of gluons produces the negative sign of the QCD beta function at high energies and leads to asymptotic freedom. Therefore, α and α_s should not be expected to have the same numerical origin.

The analogy is nevertheless useful. In standard physics, α measures the strength of electromagnetic interaction in units set by e, ε_0, $\hbar$, and c. In the proposed vacuum interpretation, α_s is not treated as a universal fixed constant but as a dimensionless efficiency coefficient associated with the color-confinement channel of a structured vacuum. This does not replace the gauge-theoretic definition in Equation (1); it proposes a physical interpretation beneath the benchmark normalization of the coupling.

A direct relation between α_s and the Newtonian gravitational constant G is not present in orthodox QCD. The reason is both conceptual and dimensional: α_s is dimensionless, whereas G has units of $\text{m}^3\cdot\text{kg}^{-1}\cdot\text{s}^{-2}$. Standard physics compares gravity and the strong interaction only after constructing dimensionless gravitational couplings, for example at the proton scale:

$$\alpha_{G,p} = \frac{Gm_p^2}{\hbar c} \simeq 5.9\times10^{-39}. \tag{7}$$

Any relation between α_s and G therefore requires an additional physical framework and a dimensionally explicit conversion between gravitational coupling and vacuum stress.

5. Origin of the Effective Strong-Force Scale

The standard short-distance color potential for a heavy quark-antiquark pair contains the Coulombic term [7],

$$V_{\text{Coulomb}}(r) = -C_F\frac{\alpha_s\hbar c}{r}, \quad C_F = \frac{4}{3}, \tag{8}$$

so that the corresponding short-distance force scale is

$$F_{\text{short}}(r) = C_F \frac{\alpha_s \hbar c}{r^2} = \frac{4}{3}\frac{\alpha_s \hbar c}{r^2}. \tag{9}$$

The factor $C_F = 4/3$ is the quadratic Casimir invariant of the fundamental representation of SU(3). It is a standard color factor, not a hydrodynamic assumption [3].

In the vortex model, a previously proposed relation connects the reduced Planck constant to the angular momentum scale of a particle-like vortex configuration [10]-[11]. In simplified form,

$$\hbar \simeq mcr, \tag{10}$$

where m is the rest-mass scale associated with the confined constituent and r is the characteristic vortex radius. Substituting Equation (10) into Equation (9) gives the model-level effective force scale

$$F_{\text{strong}}(r) \simeq \frac{4}{3}\alpha_s \frac{mc^2}{r}. \tag{11}$$

Equation (11) is not introduced as a new equation of orthodox QCD. It is a model-level reinterpretation of the color force scale in terms of energy per radius. Its purpose is to make explicit how the color-weighted coupling can be compared with a hydrodynamic resistance coefficient. A complete derivation must show precisely how Equation (10) follows from the geometry and circulation of the vacuum medium. Until that derivation is made fully explicit, Equation (11) should be presented as a motivated effective force law rather than a completed proof.

6. Definition of Vacuum Resistance and the Meaning of C_D

The expression "vacuum resistance" is used here in a restricted mechanical sense. It does not mean electrical resistance. It does not mean ordinary friction in empty space. It denotes an effective drag-like restoring stress exerted by a structured vacuum medium when a vortex-like configuration is deformed, accelerated, displaced, or separated from another vortex-like configuration.

The closest classical analogy is fluid drag, where an object moving through a medium experiences a force of the form

$$F_D = \frac{1}{2}\rho v^2 C_D A. \tag{12}$$

Here ρ is the density of the medium, v is the relative speed, A is an effective area, and C_D is a dimensionless drag coefficient. In the present model, however, C_D is not the drag coefficient of a rigid sphere, cylinder, or macroscopic object. The subnuclear configuration is treated as a vortex-like field structure. Therefore, C_D represents the efficiency with which the kinetic pressure of the structured vacuum is converted into a restoring or confining stress.

For this reason, the vacuum resistance pressure is written as

$$P_R = \frac{1}{2}\rho_{\text{vac}} c^2 C_D. \tag{13}$$

In Equation (13), ρ_{vac} is the effective density of the structured vacuum, c is the limiting propagation speed of disturbances in the vacuum medium, and C_D is the effective dimensionless resistance coefficient. The physical meaning of C_D is therefore the fraction of the available vacuum kinetic pressure that appears as an effective restoring pressure against vortex deformation or separation.

The shape dependence of C_D is not identified with a classical sphere. In the present state of the model, C_D should be understood as an aggregate geometry coefficient of a subnuclear vortex configuration. Candidate geometries include bipolar, triplet, and mushroom-like vortex structures developed in the broader vortex-vacuum program [10]-[14]. A future version of the theory must derive C_D directly from such geometry, rather than only from the hydrodynamic pressure relation.

7. Independent Hydrodynamic Derivation of C_D

The effective coefficient C_D is not obtained from QCD. It is derived first from hydrodynamic vacuum resistance.

Let P_G denote the pressure-normalized gravitational vacuum-resistance scale used in the hydrodynamic vacuum model. In the present normalization,

$$P_G = 6.67430\times10^{-11}\ \mathrm{N}\cdot\mathrm{m}^{-2}. \tag{14}$$

The numerical coefficient in Equation (14) equals the CODATA value of the Newtonian gravitational constant G in SI units, but Equation (14) must not be read as a dimensional identity between pressure and G. A dimensionally complete theory must derive the conversion factor that maps G, with units $\mathrm{m}^3\cdot\mathrm{kg}^{-1}\cdot\mathrm{s}^{-2}$, into an equivalent pressure-like vacuum-resistance scale, with units $\mathrm{N}\cdot\mathrm{m}^{-2}$. In the present article, P_G is therefore treated as a calibrated pressure scale motivated by the gravitational vacuum model, not as a proven dimensional reduction of G.

Solving Equation (13) for C_D gives

$$C_D = \frac{2P_G}{\rho_{\mathrm{vac}}c^2}. \tag{15}$$

Using

$$\rho_{\mathrm{vac}} = 9.51\times10^{-27}\ \mathrm{kg}\cdot\mathrm{m}^{-3},\quad c = 2.99792458\times10^{8}\ \mathrm{m}\cdot\mathrm{s}^{-1}, \tag{16}$$

one obtains

$$C_D = 0.15618 \simeq 0.156. \tag{17}$$

This is the decisive point: C_D is obtained before α_s is introduced. It is a hydrodynamic coefficient of the structured-vacuum model. It is not fitted to QCD and is not defined by the equation $C_D = (4/3)\alpha_s$.

Only after the hydrodynamic coefficient has been obtained do we compare it with the color-weighted strong coupling. Using the PDG benchmark value $\alpha_s(m_Z) = 0.1180 \pm 0.0009$, one finds

$$\frac{4}{3}\alpha_s(m_Z) = 0.15733 \pm 0.00120. \tag{18}$$

Thus, within the numerical accuracy of the model and the empirical uncertainty of the benchmark coupling,

$$\alpha_s^{\text{model}}(m_Z) = \frac{3}{4}C_D = 0.11713 \simeq 0.117. \tag{19}$$

The interpretation is therefore reversed relative to a fitting approach. The hydrodynamic vacuum model predicts an effective resistance coefficient near 0.156. QCD contains a color-weighted benchmark coupling near the same value. This correspondence is the central observation of the article.

8. Reverse Consistency Check

The relation can also be examined in the reverse direction, but this reverse calculation should be described as a consistency check rather than the primary derivation. If one starts from the benchmark QCD value and uses $C_D = (4/3)\alpha_s(m_Z)$, then Equation (15) gives

$$\rho_{\text{vac}}^{\text{reverse}} = \frac{2P_G}{c^2\left[(4/3)\alpha_s(m_Z)\right]}. \tag{20}$$

For $\alpha_s(m_Z) = 0.1180$, this yields

$$\rho_{\text{vac}}^{\text{reverse}} = 9.44\times10^{-27}\ \text{kg}\cdot\text{m}^{-3}. \tag{21}$$

This value differs by approximately 0.74% from $9.51\times10^{-27}\ \text{kg}\cdot\text{m}^{-3}$. The agreement is encouraging, but it should not be overstated. It demonstrates numerical self-consistency within the proposed model. It does not by itself establish a derivation of QCD from gravity or a derivation of G from QCD.

9. Asymptotic Freedom in the Vacuum-Drag Interpretation

A serious test of the model is whether it can account for asymptotic freedom. In standard QCD, α_s decreases at high momentum transfer because of the non-Abelian renormalization-group flow. The hydrodynamic vacuum model must reproduce this fact, not merely match the benchmark value at m_Z.

The natural interpretation is that the vacuum resistance coefficient is scale-dependent:

$$C_D \to C_D(Q). \tag{22}$$

If the correspondence with QCD is correct, then at scales where perturbative QCD is valid one should have

$$C_D(Q) \simeq \frac{4}{3}\alpha_s(Q) \simeq \frac{16\pi}{3\beta_0 \ln\left(Q^2/\Lambda_{\text{QCD}}^2\right)}. \tag{23}$$

The physical interpretation is that at short distances, or high Q, the probing interaction samples a smaller coherent region of the vacuum-vortex structure. The effective polarizability or resistance of the vacuum configuration decreases, so the color-vortex interaction becomes weaker. At larger distances, the coherent deformation of the vacuum increases, $C_D(Q)$ rises, and confinement emerges.

This is not yet a derivation of the QCD beta function. It is a proposed interpretation of what a successful vacuum-drag theory must produce. The model will become stronger only if it derives Equation (23), or a more accurate higher-order running law, from the dynamics of structured vacuum vortices rather than importing the QCD result.

10. Experimental, Lattice, and Falsification Tests

The proposed interpretation is scientifically meaningful only if it leads to tests that can confirm, weaken, or refute it. Several tests are especially important.

First, the model must derive the running function $C_D(Q)$ from vacuum-vortex dynamics and compare it with $\alpha_s(Q)$ across different energy scales. Agreement only at m_Z is not sufficient. The same function should account for determinations from τ decays, deep-inelastic scattering, event shapes, electroweak precision fits, collider data, heavy quarkonia, and lattice QCD.

Second, the model should predict the heavy-quark potential. In standard phenomenology, the potential includes a short-distance Coulombic term and a long-distance confining term,

$$V(r) = -C_F \frac{\alpha_s \hbar c}{r} + \sigma r, \quad C_F = \frac{4}{3}. \tag{24}$$

Here σ is the string tension. The hydrodynamic vacuum theory must reproduce both the coefficient of the Coulombic term and the string tension using one fixed set of vacuum parameters.

Third, the model implies a color-representation test. Since the correspondence involves the SU(3) color factor, sources in other color representations should exhibit an effective resistance coefficient proportional to the relevant Casimir invariant, at least in the regime where lattice QCD observes approximate Casimir scaling [15]:

$$\frac{C_D^{(R)}}{C_D^{(F)}} \simeq \frac{C_R}{C_F}. \tag{25}$$

For SU(3),

$$C_F = \frac{N_c^2 - 1}{2N_c} = \frac{4}{3}, \quad C_A = N_c = 3. \tag{26}$$

Failure to reproduce representation dependence would count against the interpretation.

Fourth, the inferred vacuum density must be used without readjustment across independent observables: G, proton mass, proton radius, hadronic string tension, spin-related proton quantities, and gravitational-scale phenomena. If each observable requires a different vacuum density or a freely adjusted C_D, the model loses predictive content.

Fifth, the dimensional mapping between G and P_G must be derived. This is essential. If the model cannot derive the conversion from the dimensions of G to a pressure-like vacuum resistance, the relation remains a numerical analogy rather than a physical derivation.

The model would be falsified or seriously weakened if it cannot reproduce the running of α_s, cannot explain Λ_{QCD} or string tension from the same vacuum parameters, fails the Casimir-scaling test, or cannot provide a dimensionally correct relation between gravitational coupling and vacuum pressure.

11. Discussion

The article does not claim that standard QCD derives from G. Nor does it claim that the accepted QCD beta function is replaced by a completed hydrodynamic theory. Instead, it proposes that the benchmark normalization of the strong coupling may correspond to an independently obtained vacuum-resistance coefficient.

The main conceptual gain is that α_s receives a possible mechanical interpretation. In standard QCD, α_s is a renormalized gauge coupling. In the vacuum-drag interpretation, α_s also measures the fraction of an independently derived vacuum resistance coefficient that appears in the color-confinement channel:

$$\alpha_s\left(m_Z\right) \simeq \frac{3}{4} C_D.$$

The factor 3/4 is not arbitrary; it is the inverse of the SU(3) fundamental color factor $C_F = 4/3$ appearing in the short-distance color force. Therefore, the model suggests that the color factor may project a more general vacuum-resistance coefficient into the specific fundamental color channel.

This interpretation is attractive because it links three ideas that are usually treated separately: vacuum structure, confinement, and gravitation. However, the link is not yet a complete theory. The most important open problems are the derivation of C_D from explicit vortex geometry, the derivation of $C_D(Q)$, the interpretation of Λ_{QCD}, and the dimensional conversion between G and P_G.

The model should therefore be judged as a falsifiable research program. Its present value lies in identifying a numerical correspondence that is not obtained by fitting C_D to α_s, but by comparing an independently calculated hydrodynamic coefficient with the color-weighted strong coupling. Its future value depends on whether this correspondence can be turned into a predictive mathematical theory.

12. Conclusions

Within standard QCD, α_s is the renormalized SU(3) gauge coupling. Its benchmark value near 0.118 at the *Z*-boson mass scale is determined from global experimental and lattice analyses and evolved through the renormalization group. It is not a universal constant valid at all scales, and no accepted standard derivation relates it directly to the Newtonian gravitational constant G.

The hydrodynamic vacuum hypothesis offers a different interpretation. In this framework, the structured vacuum has an effective density and can exert a drag-like resistance pressure against vortex deformation or separation. The effective coefficient C_D is derived first from the hydrodynamic relation $P_R = (1/2)\rho_{\text{vac}} c^2 C_D$. Using $\rho_{\text{vac}} = 9.51\times10^{-27}\ \text{kg}\cdot\text{m}^{-3}$ and the calibrated pressure-normalized gravitational vacuum-resistance scale $P_G = 6.67430 \times 10^{-11}\ \mathrm{N \cdot m^{-2}}$ gives $C_D = 0.15618$. This result is obtained independently of QCD.

The central observation is that this independently obtained value coincides numerically with the color-weighted QCD benchmark coupling, $C_D \simeq (4/3)\alpha_s(m_Z)$. Equivalently, $\alpha_s^{\mathrm{model}}(m_Z) \simeq (3/4)C_D = 0.11713$, close to the empirical value near 0.118. The relation should therefore be read as a matching correspondence between vacuum hydrodynamics and color coupling, not as an assumption used to derive C_D from α_s.

At present, the proposal remains non-standard and incomplete. It must derive the G-to-pressure conversion dimensionally, obtain the running function $C_D(Q)$, explain Λ_{QCD} as a vacuum-vortex coherence scale, reproduce lattice QCD observables such as string tension and Casimir scaling, and make predictions that cannot be reduced to post-hoc numerical agreement. If these conditions can be satisfied, the model may provide a deeper interpretation of confinement as a manifestation of structured-vacuum resistance acting on vortex-like configurations.

Conflict of Interest

The author declares that there are no conflicts of interest regarding the publication of this article.

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