**Unified Theory of Hadronic Color Singlet Structure and Mass Origin: Based on Field Combination Theory and Gluon Dynamic Compensation Mechanism**

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Abstract:  
Based on the ABC theory, this paper proposes a complete unified theory regarding the color singlet structure and mass origin of hadrons (protons and neutrons). The core argument is that the color singlet property of hadrons and the origin of the vast majority of their mass jointly arise from a dual mechanism involving the synergistic action of valence quarks and gluons:  
(a) At the valence quark level, through precise matching and annihilation of color charges (e.g., positive red charge and anti-red charge annihilation), a statistically colorless ground state is formed on average;  
(b) At the quantum level, by introducing three gluons with specific color charge combinations (their color charge combinations being positive red–anti-green, positive green–anti-blue, and positive blue–anti-red, respectively), the color charge quantum fluctuations of the valence quark ground state are dynamically compensated, thereby forming a truly stable, overall colorless hadronic state. Simultaneously, the enormous energy carried by these three gluon fields (originating from their self-interaction energy and interaction energy) contributes approximately of the hadron mass, while the rest mass of the valence quarks contributes only about . We rigorously demonstrate:  
1. Color charge matching of proton/neutron valence quarks: Through detailed color charge annihilation analysis, a statistically colorless valence quark ground state is statically constituted.  
2. Dynamic compensation by gluons and overall colorless state: The instantaneous color charge fluctuations of the valence quark state are dynamically compensated by three specific gluons, whose color current correlation functions precisely cancel out the color current fluctuations of the valence quarks, achieving dynamic balance.  
3. Origin of hadron mass: The sum of the rest masses of the valence quarks accounts for only about of the hadron mass. The vast majority of the mass (approximately ) originates from the energy of the gluon field necessary to maintain the color singlet state.

This theory unifies the color singlet structure and mass origin of hadrons under the same physical framework for the first time, elucidating that color confinement and mass generation are two manifestations of the same essence of the strong interaction.

**Keywords**: ABC theory; color singlet; valence quark matching; gluon compensation; mass origin; gluon field energy; non-Abelian interaction; color confinement

1. **Introduction**  
   The two most fundamental properties of hadrons—their color singlet structure and the origin of their large mass (approximately )—are core issues in modern particle physics. The ABC theory by Li Zhijun provides a framework for unifying these two problems. Based on this theory, this paper proposes a unified theory: the color singlet property and mass of hadrons jointly originate from the synergistic action of valence quarks and specific gluons. Valence quarks provide a static colorless foundation through color charge matching; three specific gluons maintain precise color neutrality through dynamic compensation and simultaneously provide the vast majority of the mass. Color confinement is not only the confinement of color but also the confinement of energy, and the confined energy manifests as mass.
2. **Theoretical Framework: Field Combination Theory and Color Charge Representation**  
   2.1 Overview of ABC Theory  
   The ABC theory posits that all matter in the universe is composed of three fundamental vortex fields:

* Electromagnetic vortex field (A-field): Corresponds to the gauge group, whose quantum excitation is the photon, determining electromagnetic interactions.
* Color charge vortex field (B-field): Corresponds to the gauge group, whose excitations determine the color charge and electric charge properties of particles.
* Higgs vortex field (C-field): Corresponds to the gauge group, related to mass generation.

Any particle is a specific excited combination state of these three fields.

2.2 Representation and Annihilation Rules of Color Charges  
In the ABC theory, color charges are represented by branches of the color charge field B:  
\* Positive color charge branches: each carrying a color charge value of .  
\* Anti-color charge branches: each carrying a color charge value of .

Annihilation rule: When a positive color charge encounters its corresponding anti-color charge, their color charge values algebraically sum to zero, e.g., .

1. **Valence Quark Level: Static Constitution of Color Singlet and Minimal Mass Contribution**  
   3.1 Proton (): Valence Quark Color Charge Matching and Colorless State Constitution

* Valence quark components: two up quarks (), one down quark ().
* Color charge contribution (each quark couples to two branches of the color charge field B):
  + provides color charge values:
  + provides color charge values:
  + provides color charge value:
* Color charge merging and annihilation:
  + Total color charge .
  + Among these, one and annihilate: .
  + Remaining color charge .
  + Colorimetry principle: Equal superposition of the three primary colors (R, G, B) constitutes colorlessness (white).
* Color wave function (symmetrized): [Symmetrized expression]
* Rest mass contribution: Sum of valence quark rest masses accounting for only of the proton mass ().

3.2 Neutron (): Valence Quark Color Charge Matching and Colorless State Constitution  
\* Valence quark components: one up quark (), two down quarks ().  
\* Color charge contribution:  
\* provides color charge values:   
\* provides color charge value:   
\* provides color charge value:   
\* Color charge annihilation:  
\* (red and anti-red annihilation)  
\* (green and anti-green annihilation)  
\* Remaining color charge . Directly constitutes a colorless state.  
\* Color wave function (symmetrized): [Symmetrized expression]  
\* Rest mass contribution: accounting for only of the neutron mass ().

1. **Quantum Level: Dynamic Compensation by Gluons and Formation of the Overall Colorless State**  
   The aforementioned valence quark color singlet is an overall average result. In quantum field theory, field values are operators and exhibit quantum fluctuations. Therefore, the instantaneous color charge of valence quarks is not strictly zero, i.e., .

To form a true, stable overall colorless state, a dynamic compensation mechanism must be introduced.

4.1 Introduction of Three Specific Gluons  
We introduce three specific gluons with color charge properties as follows:  
\* Gluon : , carrying color charge .  
\* Gluon : , carrying color charge .  
\* Gluon : , carrying color charge .

Key properties:  
1. Overall color neutrality: As a whole, the three gluons have a total color charge: .  
2. Color charge complementarity: Their color charge combinations exhibit strong complementarity with the color charge pattern of the valence quark singlet state.

4.2 Mechanism of Dynamic Compensation: Yang-Mills Equations and Constraints  
The dynamics of the gluon field are described by the Yang-Mills equations:

where is the color current of the valence quarks.

This equation is a constraint. Its time component () in the instantaneous Coulomb gauge gives:

This equation shows that the distribution of the gluon field is instantaneously determined by the color charge density of the valence quarks The gluon field adaptively adjusts its configuration in response to changes in the quark color charges.

4.3 Cancellation of Quantum Fluctuations: Correlation Function Level  
At the quantum level, the maintenance of color neutrality is reflected in the cancellation of correlation functions. Consider the expectation value of the two-point correlation function of the total color current on the physical state (color singlet):

Decomposing it:

This means that the quantum fluctuations of the gluon color current and its cross-correlation with the quark color current precisely compensate for the fluctuations of the quark color current

1. **Origin of Hadron Mass: Dominance of Gluon Field Energy**The small proportion of the sum of valence quark rest masses () indicates that the mass of hadrons must have another origin. We propose that the mass primarily originates from the energy carried by the gluon field introduced to maintain the color singlet state.

5.1 Energy-Momentum Tensor of the Gluon Field  
The energy of the gluon field is given by the Hamiltonian density of the Yang-Mills action:

where is the color electric field and is the color magnetic field. The introduction of three specific gluons implies the existence of a non-trivial, highly energy-concentrated gluon field configuration inside the hadron.

5.2 Non-Abelian Self-Interaction and Energy Scale  
The key point is that the gluon field is non-Abelian. Its field strength tensor contains a self-interaction term This term is nonlinear, allowing the gluon field to self-sustain even without external sources. Its energy scale is determined by the QCD characteristic scale

5.3 “Energy Bag” Picture and Mass Generation  
The interior of a hadron can be viewed as an “energy bag.”  
1. Gluon field energy: The gluon field strength inside the bag is so the energy density Integrating over the hadron volume the energy contributed by the gluon field is .  
2. Quark kinetic energy: Valence quarks are confined within a bag of radius so their momentum uncertainty is Their kinetic energy is The total kinetic energy of three quarks is .  
3. Interaction energy: The interaction between valence quarks and gluons also contributes energy.

The sum of and is on the order of consistent with the proton mass. Among these, the gluon field energy is the dominant contribution.

1. **Conclusion: Unified Picture**Within the framework of the ABC theory, this paper proposes a unified theory of hadron structure and mass origin:

1. Structural aspect: The color singlet of hadrons is constituted by the static matching of valence quarks and dynamic compensation by gluons.

2. Mass aspect: The mass of hadrons primarily () originates from the energy of the gluon field necessary to maintain the color singlet state.

3. Intrinsic unity: Color confinement and mass generation are two manifestations of the same essence of the strong interaction. Color confinement requires the existence of specific gluon fields, and the energy of these gluon fields manifests as mass.

This theory provides a self-consistent, profound, and unified physical framework for understanding the fundamental properties of hadrons.

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