The Field Combination Mechanism of Quark Confinement: A Theory Based on Color Charge Field Branch Entanglement and Topological Constraints

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Abstract:  
Based on Professor Li Zhijun’s ABC theory, this paper proposes a novel interpretation of the essence of quark confinement. The core argument is that quark confinement does not originate from some mysterious “confining force,” but rather emerges as an inevitable, holistic field combination state resulting from topological entanglement and self-interactions of specific branches of the color charge vortex field at the hadronic scale. We demonstrate that the field combination of a single quark, cannot exist as an asymptotic state because its color charge field branch is topologically non-trivial, leading to a divergence of its field energy density at spatial infinity. Only when the color charge field branches of multiple quarks form specific holistic entangled states (e.g., the baryonic or the mesonic can color singlet states be constructed, causing the total color charge field to decay exponentially outside the hadron, resulting in finite energy. We construct an entanglement entropy operator for the color charge field branches to describe this process and prove that the physical essence of confinement is the localization of quantum information from the color charge field branches within the hadron, preventing its propagation to infinity via the color current This model treats confinement as a holistic, topologically protected quantum phenomenon, providing a deeper physical picture for understanding strong interactions.

Keywords: ABC theory; Quark confinement; Field combination; Color singlet; Topological entanglement; Quantum information localization; Color current

1. Introduction: Redefining the Physical Picture of Confinement

“Quark confinement” is one of the most profound problems in the Standard Model. The traditional picture describes it as “color flux lines” being squeezed into “strings,” leading to a potential energy that grows linearly with distance (). However, this force-based picture does not reveal its most fundamental origin. Based on the ABC theory, this paper proposes that the essence of confinement lies in the topological instability of the quantum state of the color charge field outside hadrons. Only specific multi-body entangled states (color singlets) can form stable, finite-energy field combinations.

1. Theoretical Framework: Topological Non-Triviality of a Single Color Charge Field Branch

2.1 Field Combination of a Single Quark and Its Problem

The field combination of a quark (e.g., a red up quark) is:

Its color charge field part indicates the excitation of the red branch. This excited state acts like a “color charge source,” whose field strength at large distances satisfies:

Leading to its field energy:

Diverges! This means a field combination state with non-zero net color charge has infinite energy and cannot physically exist as a stable asymptotic state. This is the mathematical formulation of confinement: non-zero color charge states cannot be observed.

2.2 Field Combination Criterion for Confinement

Physically allowed, finite-energy states must satisfy:

This requires the total color charge of the system to be zero, i.e., it must be a global color singlet.

1. Formation of Color Singlets: Entanglement and Neutralization of Color Charge Field Branches

3.1 Baryonic Color Singlet Formation: Complete Antisymmetric Entanglement of Branches

The raw direct product state of three quarks (e.g., proton uud) is:

This state is not a color singlet; its energy diverges.

By introducing complete antisymmetric entanglement (projection operator we obtain the physical color wavefunction of the proton:

This state is a singlet under the group: for any group element , This means that outside the hadron, the excitations of the overall color charge field cancel each other out, the field strength decays exponentially, and the energy is finite.

3.2 Mesonic Color Singlet Formation: Particle-Antiparticle Neutralization of Branches

The direct product state of a quark-antiquark pair is:

By introducing color neutralization entanglement (projection operator the physical meson color wavefunction is obtained:

This state is also a color singlet, overall colorless.

1. Dynamical Mechanism of Confinement: The Roles of Gluon Fields and Color Currents

4.1 Gluon Fields: The “Binder” of Color Charge Field Branches

The gluon field combination itself carries color charge. They are constantly exchanged between quarks, and their role is to maintain the overall color singlet entangled state.

Image: Imagine three quarks, each trying to emit colored gluons. But the emission and absorption of gluons must keep the entire system in a color singlet state. Any attempt to pull a single quark away forces the connecting gluon field flux tubes to readjust, consuming enormous energy to maintain overall color neutrality, manifesting as the potential.

4.2 Color Current Conservation and Information Localization

Confinement is dynamically ensured by color current conservation. The divergence of the color current is zero, This means color charge cannot be created or destroyed, only transferred.

In the ABC field combination theory, this means the quantum information of the color charge field branches cannot be localized on a single quark. Attempting to separate a quark is attempting to localize the color charge information encoded in the holistic entangled state to a point, which requires an infinite entropy change and is impossible from an information theory perspective. Therefore, the color charge information is permanently confined within the hadron.

1. Mathematical Modeling: Color Singlet Projection and the Mass Gap

5.1 Color Singlet Projection Operator

The color singlet projection operator for baryons is:

This operator projects any three-quark state onto the unique color singlet state.

5.2 Origin of the Mass Gap

Confinement implies the existence of a mass gap : the energy of any colored excitation (e.g., a single quark) is at least while the energy of color singlets (hadrons) can be low.

From the field combination perspective, this is because constructing a color singlet requires specific entanglement, while constructing a non-singlet implies exciting high-energy modes of the color charge field. is essentially the characteristic energy scale at which the color charge field undergoes self-interactions leading to topological stability.

1. Conclusion: Confinement as a Holistic Topological Phenomenon

Based on the ABC theory, this paper reveals the new physical essence of quark confinement:

6.1.Root of Confinement: The excitation of a single color charge field branch is topologically non-trivial, its energy diverges, so it cannot exist alone.

6.2.Condition for Deconfinement: Only when the color charge field branches of multiple quarks form a holistic entangled state (color singlet) can the total color charge be zero, resulting in finite energy.

6.3.Physical Picture of Confinement: Confinement is not a “force,” but an inevitable consequence of the inability to localize color charge information from a multi-body entangled state. A hadron is a “black hole” for color charge information; information cannot escape in the form of color charge.

6.4.Role of Gluons: Gluons are the excitation quanta of the color charge field branches; their exchange maintains the overall color singlet state and provides the linear term of the confining potential.

This model elevates confinement from a phenomenological force problem to a fundamental physical problem concerning quantum field topology and quantum information, providing a deeper framework for ultimately understanding strong interactions.

References  
[1] Li, Z. J. (2023). The ABC Mechanism in the Universe.  
[2] Wilson, K. G. (1974). Confinement of Quarks. Physical Review D, 10(8), 2445–2459.  
[3] ’t Hooft, G. (1981). Topology of the Gauge Condition and New Confinement Phases in Non-Abelian Gauge Theories. Nuclear Physics B, 190(3), 455–478.  
[4] Nambu, Y. (1974). Strings, Monopoles, and Gauge Fields. Physical Review D, 10(12), 4262–4268.  
[5] Witten, E. (1979). Current Algebra, Baryons, and Quark Confinement. Nuclear Physics B, 160(1), 57–115.