Characteristic Behavior of Color Flux-Tubes in Dual QCD

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The complexities associated with strong interaction [1, 2] could be described in terms of Quantum Chromodynamics (QCD) that describes the hadrons in terms of quarks and gluons. QCD acheieved a remarkable success in its high momentum transfer region due to asymptotic freedom. However, the quarks and gluons have never been found in isolation so far which commonly attributed as quark confinement in QCD. Such peculier feature attracts a great deal of interest but no rigorous and sound theoretical formulation could be found so far. To address the color confining behavour of non-trivial QCD vacuum, a gauge independent field theoretical formulation based on magnetic symmetry [3],[4]-[8] has been developed and extended further to discuss the phase structure of QCD vacuum [4]-[8]. In the present study we have briefly summarised the field theoretical description of QCD vauum at zero temperature where the appearence of color flux-tubes plays a vital role to explicate the non-perturbative features like confinement, chiral symmetry breaking etc. The true behavior of non-trivial QCD vacuum has also been discussed in different hadronic scales (specially in Bogomol'nyi limit) alongwith the implications of color flux-tube interaction in phase transition and QGP formation.
Consider the SU(2) QCD for simplicity, and choosing $\hat{n}$ to be the arbitrary color direction in magnetic gauge and impose the gauge covariant magnetic symmetry condition, $D_\mu \hat{n} = 0$, to project out the color neutral Abelian (dual) potential as

$$\hat{W}_\mu = A_\mu \hat{n} - g^{-1}(\hat{n} \times \partial_\mu \hat{n}), \qquad (1)$$

where the first term corresponds to the non-topological Maxwellian part which describes the colored neutral gluons (neuron) while the second one which is topological in origin describes the non-Abelian monopoles and corresponds to the homotopy class of the mapping $\Pi^2(S^2)$ of the two dimensional spatial sphere S^2_R to the group coset space $S^2 = SU(2)/U(1)$ of the internal space. Such decomposition brings duality further at the level of field strength with $G_{\mu\nu} = (F_{\mu\nu} + B^{(d)}_{\mu\nu})\hat{n}$ where $F_{\mu\nu} = A_{\nu,\mu} - A_{\mu,\nu}$ and $B^{(d)}_{\mu\nu} = -g^{-1}\hat{n}.(\partial_\mu \hat{n} \times \partial_\nu \hat{n}) = B_{\nu,\mu} - B_{\mu,\nu}$. The second part (B_μ), fixed completely by $\hat{n}$, is thus identified as the magnetic potential associated with the topological monopoles and the fields thus appear in a completely dual symmetric way. Under these considerations one can, therfore, construct the following gauge invariant dual QCD Lagrangian in quenched approximation as,

$$\mathcal{L}^{(d)}_m = -\frac{1}{4}B^2_{\mu\nu} + |[\partial_\mu + i\frac{4\pi}{g}B^{(d)}_\mu]\phi|^2 - 3\lambda\alpha_s^{-2}(\phi^*\phi - \phi_0^2)^2 \qquad (2)$$

The relevant choice of the effective potential for inducing the dynamical breaking of magnetic symmetry, in turn leads to the magnetic condensation of QCD vacuum resulting from dual Meissner effect with the appearence of color flux tubes that confine the color isocharges. Such Nielson and Olenson vortex [9] like flux tube structure can be realized in tems of the associated field equations $\mathcal{D}^\mu \mathcal{D}_\mu \phi + 6\lambda\alpha_s^{-2}(\phi^*\phi - \phi_0^2)\phi = 0$ and $\partial^\nu B_{\mu\nu} = k_\mu$. This further sts two characterictic mass scales in magnetically condensed QCD vacuum. One is notioned as vector mode m_B and basically define the screening length of color electric flux inside the QCD vacuum. The other one is identified as scalar mode (m_ϕ) and determines the coherence length of condensed magnetic pair. Their ratio (which is fixed by effective potential) in terms of dual Gingburg Landau

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parameter ($\kappa^{(d)}$) characterize the dual QCD vacuum in type-I and type-II category [4]. For $\kappa^{(d)} < 1$, the QCD vacuum behaved as type-II whereas for $\kappa^{(d)} > 1$ it shows its type-I character. However, the $k^{(d)}$ =1 is the critical Bogomol'nyi limit which corresponds to the transition boundary between type-I and type-II vacuum and has interesting implications in dual QCD phase transition. For that purpose let us consider the flux-tube energy per unit length [7, 8] which in the asymptotic limit acquires the following form for the cylindrical system

$$k = 4\pi n\phi_0^2 \tag{3}$$

subjected to the condition $2\Omega = \frac{n^2}{\Lambda^2}$ in the asymptotic limit where $\Omega = 3\lambda\alpha_s^{-2}$ and $\Lambda = (ng/4\pi)$. This is nothing just but the condition where both the mass modes are equal i.e. $m_B = m_\phi$ corresponds to $= 1$. The associated DGL parameter ($\kappa^{(d)}$) is unity here and set a critical limit dubbed as dual Bogomol'nyi limit that separates the dual QCD vacuum into type-I and type-II category. This categorization of QCD vacuum leads the characteristic behavior of associated color flux tubes specifically how do they interact in different hadronic range. For SU(2) case, consider a color flux-tube bearing the color charges $ne_c/2$ and -$ne_c/2$ at its ends where 'n' is the winding number. In this system, the interaction energy is defined as $\varepsilon_{int} = \varepsilon_{total} - 2 \times \varepsilon_{single}$ which

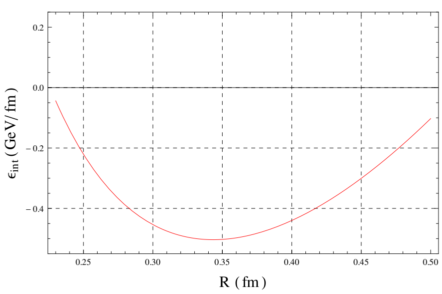

FIG. 1: (color online) Flux-tube interaction energy as a function of distance

in the dual Bogomol'nyi limit becomes zero due to the balance of the interaction range of both mass modes m_B (mass of dual gauge field) and m_ϕ (mass of monopole field). In the type-I and type-II vacuum, the imbalance arises in their interaction ranges and consequently the existing flux tube interact accordingly. This, in fact, put forward an interesting panorama of phase transition and QGP formation on theoretical ground that may cosists well with the recent heavy-ion collision experiments. In ultrar-relativistic heavy-ion collision experiments (little bang) where multi-flux tube system is expected to produce in the pre-equlibrium stage just after collisions, there is the possibility of QGP formation that depends on the energy deposition within 1 fm/c. In the present dual QCD model at the large hadronic distance ($\alpha_s = 0.96$) as shown in figure the annihilation between two color flux-tubes would takes place with a large amount of liberation energy $\varepsilon_{lib} = 14.5\ GeV/fm$ which can make a significant contribution to the QGP phase transition through flux-tube annihilation process in the central region where expected flux tube density is sufficiently high.

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