Finite Temperature Confinement-Deconfinement Phase Transition in Dual QCD

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Flux tubes in QCD play important roles in many interesting phenomena like confinement of quarks, quark pair creation, hadron structure and phase transitions. In the dual superconductor picture of confinement, the color flux tube is formed due to the dual Messiner effect caused by monopole condensation [1]. The resulting potential is linear and consequently leads to color confinement. QCD flux tubes are also well studied in the formation of confinement-de-confinement phase transition at finite temperatures [2].

The present paper, provides a new description for the QCD flux tubes and the confinement-deconfinement phase transition at finite temperature. Our formulation is based on a new set of variables in non-Abelian gauge theories [3,4] where, usual gauge potential W_μ splits into two new gauge potentials A_μ and B_μ, which are quit convenient and efficient in studying the confinement phenomena. The part B_μ of the potential is identified as the magnetic potential and is completely determined by magnetic symmetry. Further, in order to avoid the problems due to the point-like structure and the singular behavior of the potentials associated with monopoles, we use regular dual magnetic potential B_μ^d for the topological part and introduce a complex scalar field ϕ for the monopole. Now, to study the confining properties of dual QCD [4] under above consideration, the lagrangian in quenched approximation may be written as

$$L = -\frac{1}{4}B_{\mu\nu}^2 + \left|\left(\partial_\mu + i\frac{4\pi}{g}B_\mu^d\right)\phi\right|^2 - V(\phi^*\phi), \qquad (1)$$

where, $B_{\mu\nu} = B_{\nu,\mu}^d - B_{\mu,\nu}^d$, is the dual gauge field strength and $V(\phi^*\phi) = \Omega\left(\phi\phi^* - \phi_0^2\right)^2$ is the effective potential with $\phi_0^2 = \langle\phi^*\phi\rangle$ as the vacuum expectation value of ϕ field. $\Omega = 3\lambda/\alpha_s^2$ being a constant quantity with $\alpha_s = g^2/4\pi$ as the strong coupling constant. Because of the appearance of dual magnetic potential and the monopole field in equation (1), the dynamical breaking of the magnetic symmetry by effective potential, forces the magnetic condensation and leave the QCD vacuum in a state of magnetic (dual) superconductivity which, with the formation of flux tubes, confine any color electric sources present.

In order to study the flux tube structure of dual QCD vacuum, let us choose the ansatz for cylindrical symmetric solutions as $B^d(\rho,\varphi) = \hat{\varphi}B(\rho), \phi(\rho,\varphi) = \exp(in\varphi)\chi(\rho)$ and the corresponding field equations in terms of these functions may be written in the following form

$$\chi'' + \chi'\rho^{-1} + (n\rho^{-1} + 4\pi g^{-1}B)^2\chi + 2\Omega\chi(\chi^2 - \phi_0^2) = 0, \qquad (2)$$

$$B'' + B'\rho^{-1} - B\rho^{-2} - 8\pi\ g^{-1}(n\rho^{-1} + 4\pi g^{-1}B)\chi^2 = 0, \qquad (3)$$

where, the primes denotes differentiation with respect to ρ. By defining the dimensionless ratio and functions as, $r = 2\sqrt{\Omega}\phi_0\rho,\ F(r) = 4\pi\rho g^{-1}B(\rho),$ and $H(r) = \chi(\rho)\phi_0^{-1}$, alongwith imposing the boundary conditions, $F \to 0,\ H \to 0$ as

$r \to 0$, and $F \to$ -n, $H \to 1$ as $r \to \infty$, the regular solutions of equations (2) and (3) for large values of r may be obtained as,

$$H(r) = 1 - AK_0(r), \quad (4)$$

$$F(r) = -n + BrK_1(\sqrt{\gamma} r), \quad (5)$$

where, K_0 and K_1 are modified Bessels functions and the regular solution for dual gauge field is given by

$$F(\rho) = -n + \delta\rho^{1/2} \exp(-m_B \rho), \quad (6)$$

where, $\delta = B\pi\sqrt{12\sqrt{2}\phi_0 / g^3}$ being a constant and m_B is the mass of vector glueball in condensed QCD vacuum and is given by $m_B = (2\sqrt{2\pi}\phi_0)/\sqrt{\alpha_s}$. Equation (6) clearly shows that the color electric field penetrates the dual QCD vacuum upto a depth of $(m_B)^{-1}$. The ratio of the two characteristic mass scales as fixed by the effective potential is given by $m_\chi / m_B = \sqrt{3\lambda}(2\pi\alpha_s)^{-1/2}$ leads the mass of scalar glueball as $m_\chi = (2\sqrt{3\lambda}\phi_0)/\alpha_s$. The energy per unit length (string trnsion) of the flux tube $k = \gamma\varphi_0^2$ (where γ dimensionless parameter) and the Regge slop parameter $\alpha' = (2\pi k)^{-1} = (2\pi\gamma\phi_0^2)^{-1}$, leads the value of ϕ_0 as 0.147 *GeV* for $\alpha_s = 0.22$, $\lambda = 1$ and $\gamma = 7.89$. Using the value of ϕ_0, we get the numerical estimate of characteristic masses as $m_B = 1.57$ *GeV* and $m_\chi = 2.32$ *GeV.*

Further, to study the confinement-de-confinement phase transition at finite temperature T, by using Dolan and Jackiw approach [5], the effective potential at finite temperature may be formulated as

$$V(\bar{\phi}, T) = 2\Lambda\phi^2\bar{\phi}^2 + \Lambda\bar{\phi}^4 + 4\Lambda\phi_0^4 - (\pi^2/15)T^4) + (2T^2\Lambda/3)\begin{bmatrix}(\bar{\phi}^2 - \phi_0^2) + \\ \pi\alpha_s\bar{\phi}^2\end{bmatrix}, \quad (7)$$

where, for the temperature dependent effective potential, we may shift ϕ field as $\phi \to \phi + \bar{\phi}$ in the lagrangian given by equation field (1) and $\Lambda = 3\lambda / 4\alpha^2$ as a constant quantity. Using the above expression, the behavior of QCD monopole condensate at finite temperature is formulated as

$$\langle\phi\rangle_T = \sqrt{\phi_0^2 - \{(1 + \pi\alpha_s)/3\}\,\mathrm{T}^2},$$

which shows that the monopole condensate disappears above $T = 0.195\,GeV$ and the analysis of the above expression confirms a second order QCD phase transition. The critical temperature of the confinement-deconfinement phase transition may be obtained by putting the coefficients of $\bar{\phi}^2 = 0$ in equation (7) as following

$$T_C = \sqrt{3}(1 + \pi\alpha_s)^{-1/2}\phi_0, \quad (8)$$

which also confirms that the critical temperature of the confinement-deconfinement phase transition is $T_C = 0.195$ *GeV.* Finally the masses of vector and scalar glueball at finite temperature may be expressed as

$$m_B(T) = 2\sqrt{2\pi}(\alpha_s)^{-1/2}\langle\phi\rangle_T,$$

$$m_\chi(T) = 2\sqrt{3}\,(\alpha_s)^{-1}\langle\phi\rangle_T, \quad (9)$$

which shows a large reduction of glueball masses near critical temperature $T_C = 0.195$ *GeV* as $m_B(T) = 0.15$ *GeV* and $m_\chi(T) = 0.22$ *GeV* for $\lambda = 1$. Such value of T_C is equivalent to the cut off limit of QCD scale $\Lambda_{(\overline{MS})} = 0.2\,GeV$, which pushes the QCD vacuum in QGP phase.

References

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