Polyakov Loop and recombination dynamics of quarks and gluons

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Introduction:

The Polyakov loop plays the role of an order parameter for confinement-deconfinement phase transition in QCD. This loop $\hat{L}$ is a matrix in color space given by

$$\hat{L}(\vec{x}) \; = \; \mathcal{T} \exp \left[-i \int_0^\beta dx_4 A_4(x_4, \vec{x}) \right] , \quad (1)$$

with $\beta = 1/T$ the inverse temperature and $A_4 = iA^0$.

Here we construct the partition function where the gluon field is a quantum fluctuation over a constant background[1]. We obtain the thermodynamic potential of a gas of quarks, anti-quarks and gluons and try to understand the physical implications of the quark-gluon phase transition.

In presence of Polyakov loop (background temporal gauge field A_0) the thermodynamic potential [1–4] is

$$\begin{aligned} \Omega \; &= \; \Omega_q + \Omega_{\bar{q}} + \Omega_g \\ &= \; -2N_f T \int \frac{d^3p}{(2\pi)^3} \mathrm{tr} \ln \left[1 + \hat{L}_F \, e^{-(E_q - \mu)/T} \right] \\ &\quad -2N_f T \int \frac{d^3p}{(2\pi)^3} \mathrm{tr} \ln \left[1 + \hat{L}_F^\dagger \, e^{-(E_q + \mu)/T} \right] \\ &\quad +2T \int \frac{d^3p}{(2\pi)^3} \mathrm{tr} \ln \left(1 - \hat{L}_A \, e^{-E_g/T} \right) , \quad (2) \end{aligned}$$

where F and A correspond to the 'fundamental' and 'adjoint' representation of $SU(N_c)$ color gauge group, respectively. Number of flavor N_f along with 2 spin states for fermions, and 2 states of polarization for gluons are also taken into account. Now, one can also write the gauge invariant Polyakov Loop fields normalized by the dimension of the respective representations, as

$$\Phi = \frac{1}{N_c} \mathrm{tr} \hat{L}_F \, , \qquad \bar{\Phi} = \frac{1}{N_c} \mathrm{tr} \hat{L}_F^\dagger \, , \qquad \Phi_A = \frac{1}{N_c^2 - 1} \mathrm{tr} \hat{L}_A \, , \quad (3)$$

where $\hat{L}_F$ and $\hat{L}_A$ are the Polyakov loop matrices in the fundamental and adjoint representations respectively. Also the auxiliary field associated with the adjoint representation, Φ_A is related to those of fundamental representation Φ and $\bar{\Phi}$ as

$$\left(N_c^2 - 1 \right) \Phi_A = N_c^2 \bar{\Phi} \Phi - 1 \, . \quad (4)$$

The Polyakov loop field in fundamental representation transforms under the global $Z(N_c)$ symmetry as

$$\Phi \to e^{2\pi i/N_c} \Phi \, . \quad (5)$$

For confined phase below T_c, $\Phi \to 0$ and the $Z(N_c)$ symmetry is unbroken. On the other hand with the plasma temperature above T_c, $\Phi \neq 0$ and the $Z(N_c)$ symmetry is spontaneously broken.

Matter Sector:

Now, from (2) the thermodynamic potential for quarks and anti-quarks of N_f flavors with two spin states in presence of background Polyakov Loop fields can be calculated.

We could show that $Z(N_c)$ symmetry is explicitly broken with quarks under the rotation in (5), since they carry the $Z(N_c)$ charge. Now we know that $\Phi(\bar{\Phi})$ is unity at $T \to \infty$ (deconfined phase) and vanishes at $T \leq T_c$ (confined phase). We investigate the characteristics of the quark-antiquark potential in these two extremes cases.

In the high temperature limit it leads to a free gas of quarks and anti-quarks. On the other hand in the low temperature limit the Polyakov loop dynamically confines three colored quarks in the same energy state, which finally forms a color neutral object like a baryon. Mesonic states are also formed if one combines the arguments of the logarithm of quark and anti-quark thermodynamic potential in (2). This observation is in conformation with the recombination model of hadronisation in heavy ion collisions[5].

Gauge Sector in a Hot Matter:

In the same way we can calculate the thermodynamic potential of the transverse gluons (*i.e.*, foreground gluons) in presence of background Polyakov Loop fields using (2). Here also we investigate the characteristics of the thermodynamic potential of gluons for two extreme cases, i.e., at $T \to \infty$ and at $T \leq T_c$.

In asymptotically high temperatures ($T \gg T_c$), taking the limit $\Phi, \bar{\Phi} \to 1$, corresponding to $A_0 \to 0$, we find the thermodynamic potential of free gluon with color degree of freedom. Thus, we get back the standard expression for a non-interacting gas of gluon.

In the low temperature ($T \leq T_c$) and $\Phi \to 0$, we observe that the Polyakov loop confines N_c number of gluons in the same energy state representing a color neutral glue-ball and there are two such copies. This is in accordance with $SU(N_c)$ color gauge theory. On the other hand the two remaining transverse gluons pick up the phase factor of $Z(N_c)$ symmetry which are conjugate to each other but lead to an ionization of $Z(N_c)$ charge. This basically indicates that these foreground gluons get connected to the background.

References

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