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Full Length Research Paper

A study on the deconfined degree of freedom (g_1) and the running coupling constant ($\alpha_s(T)$)

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The quark-gluon plasma is a novel state of matter in which quarks are no longer confined to bound states such as baryons and mesons. the freezing of quark–gluon deconfined degrees of freedom is the essential ingredient in determining the conditions in a transition between phases that has time to develop into equilibrium. The degree of freedom in the confined hadronic matter phase and the deconfined phase, that is, the QGP, is important in the study of phase transition in the early universe. It is calculated according to the strong coupling constant. But in the present work, we try to figure out the effect of the running coupling constant in the calculation of the degree of freedom, the latent heat and the critical pressure in the confined-deconfined phase of matter.

Key words: Degree of freedom, confined phase (hadronic matter), deconfined phase (QGP), strong coupling constant, running coupling constant.

INTRODUCTION

The strong coupling constant, α_S, is one of the fundamental parameters of the Standard Model of Particle Physics. The energy dependence of α_S is predicted by the renormalization group equation (RGE). The value of α_S has been determined in many different processes, including a large number of results from hadronic jet production, in either e^+e^- annihilation or in deep-inelastic *ep* scattering (DIS) up to energies of ~209 GeV (Wobisch, 2011). In quantum chromodynamics (QCD), one has a single coupling constant g_s, or the usually more convenient $\alpha_S = \frac{g_S^2}{4\pi}$, and various quark masses m_f with f = u, d, ..., t. One refers to their dependence on μ in the framework of a given renormalization scheme (RS) ($\alpha_S(\mu^2)$, $m_f(\mu^2)$,...) as to the running coupling constant to the running masses, etc., (Prosperi et al., 2006). The 'freezing' of quark–gluon 'color' deconfined degrees of freedom is the essential ingredient in determining the conditions in a transition between phases that has time to develop into equilibrium. The following discussion tacitly assumes the presence of latent heat *B* in the transition, and a discontinuity in the number of degrees of freedom, g_2 = g_1, where '1' refers to the primeval quark-gluon plasma (QGP) phase and '2' to the final hadronic-gas state (Letessier and Rafelski, 2004).

The polarization of QCD vacuum causes a variation of the physical coupling under changes of distance ~ 1/*Q*, so QCD predicts a dependence $\alpha_S = \frac{g^2}{4\pi} = \alpha_S(Q)$.

This dependence is described theoretically by the renormalization group equations and determined experimentally at relatively high energies. However, the well-established conventional perturbation theory cannot be used effectively in the infrared (IR) domain. Meanwhile, there exists a phenomenological indication in favor of a smooth transition from short distance to long distance physics (Ganbold, 2011).

QCD PROPERTIES

Confinement

The color singlet states exist only in QCD vacuum (hadronic world), and represented by quark-antiquark bound states (mesons) and

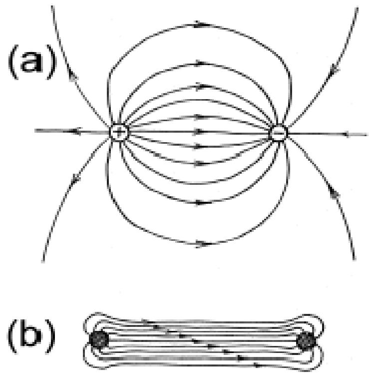

Figure 1. The electric field lines in the vacuum (a) and in dielectric medium (b).

three-quarks (antiquarks) bound states (baryons and antibaryons) (Mahmoud, 2004). This suggests that the interactions between quarks and gluons must be strong at large distance scales and the potential between quarks increases with the quark separation.

As the shown in the work of Mrowczynski (1998), the electric field generated by the two opposite charges which are in the normal vacuum (Figure 1a) and in the dielectric medium (Figure 1b). Let us imagine that one tries to burst the meson up separating the quark from the antiquark. Stretching the meson requires pumping of the energy to the system. When the energy is sufficient to produce the quark–antiquark pair, the string breaks down and we have two mesons instead of one (Mrowczynski, 1998).

Asymptotic freedom

As the quarks within a meson or baryon get closer together, the force of confinement gets weaker so that it asymptotically approaches zero for close confinement. The implication is that the quarks in close confinement are completely free to move around. Asymptotic freedom states that the coupling constant, which characterizes the strength of the quark gluon interaction in QCD, becomes weak at large relative momenta or at short distances (Sundaresan, 2001). The interaction between particles mediated by the gauge fields vanishes as the distance between the particles tends to zero (or the square of the four-momentum transferred between the particles tends to infinity). Since the particles behave as free particles in the asymptotically high energy region, this behavior is called asymptotic freedom. This feature provides a natural explanation for the parton model of hadrons (Sundaresan, 2001).

The quark, quark coupling strength decreases for small values of r, as a result of the penetration of the gluon cloud surrounding the quarks (Rohlf and William, 1994). The gluons carry "color charge" and therefore the penetration of the cloud would reduce the effective color charge of the quark.

PHASE TRANSITION POINT

To find the phase transition point, one determines the (critical) temperature at which the pressures in the two phases are equal. One allows, in a transition of first order, for a difference in energy density $\varepsilon_1 \neq \varepsilon_2$ associated with the appearance of latent heat *B* (the 'bag constant'), which also enters the pressure of the deconfined phase (Letessier and Rafelski, 2004). One considers the Stefan Boltzmann pressure of a massless photon-like gas with degeneracy.

$$P_c \equiv P_1(T_c) = \frac{\pi^2}{90} g_1 T_c^2 - B \qquad (1)$$

$$P_c \equiv P_2(T_c) = \frac{\pi^2}{90} g_1 T_c^4 \qquad (2)$$

Then, one obtains the latent heat:

$$\frac{B}{T_c^4} = \frac{\pi^2}{90} \Delta g \qquad (3)$$

$$T_c = B^{1/4} \left(\frac{\pi^2}{90} \Delta g \right)^{1/4}, \Delta g = g_1 - g_2 \qquad (4)$$

For the pressure at the transition temperature T_c, one can determine the critical pressure, P_c:

$$P_c = B \frac{g_2}{\Delta g} \qquad (5)$$

The pressure, and therefore, the dynamics of the transition in the early universe, depends on the presence of non-hadronic degrees of freedom, which are absent from laboratory experiments with heavy ions. In summary, the phase-transition dynamics in the early universe is determined by:

1. The effective number of confined degrees of freedom, g_2 at T_c.
2. The change in the number of acting degrees of freedom Δg, which occurs exclusively in the strong-interaction sector.
3. The vacuum pressure (latent heat) *B*, a property of strong interactions.

Both phases involved in the hadronization transition contain effectively massless electro-weak (EW) particles. Even though the critical temperature does not depend on the background of EW particles not participating in the transition, the value of the critical pressure (Equation 5) depends on this, and thus to consider the active electro-weak degrees of freedom. These involve photons, γ, and all light fermions, namely, *e*, μ, ν_e, ν_μ and ν_τ (one excludes the heavy τ -lepton with $m_\tau >> T$ and one considers the muon as being effectively a massless particle). Near to $T \approx$ 200 MeV, one obtains:

$$g^{EW} = g_\gamma + \frac{7}{4} g_F^{EW}, g_\gamma = 2 \qquad (6)$$

and

$$g_F^{EW} = \frac{7}{8} \times 2 \times \left(2_e + 2_\mu + 3_\nu \right) = 12.25 \qquad (7)$$

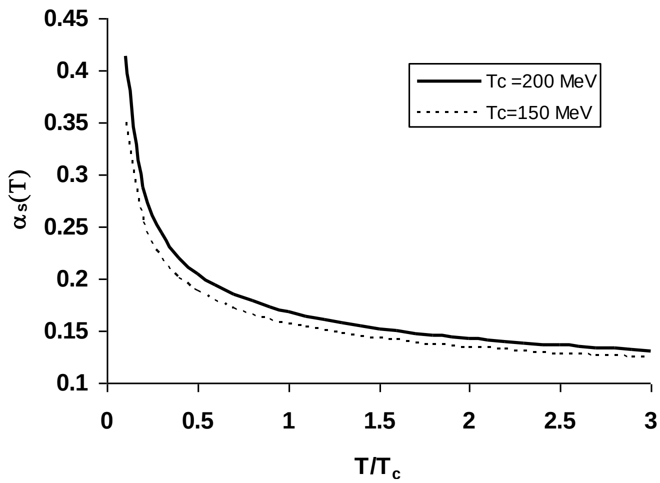

Figure 2. The running coupling constant $\alpha_s(T)$ versus T/T_c and at different critical temperature T_c= 150, 200 MeV, n_f=2.

where charged, effectively massless fermions enter with spin multiplicity 2, and one has three neutrino flavors, that is, there are only left-handed light neutrinos and right-handed antineutrinos, and thus, only half as many neutrino degrees of freedom would naively be expected. In the deconfined QGP phase of the early universe, one has:

$$g_1 = g^{EW} + g_g + \frac{7}{4} g_q \qquad (8)$$

The number of effectively present strongly interacting degrees of freedom of quarks and gluons is influenced by their interactions, characterized by the strong coupling constant as,

$$g_g = 2_s \times 8_c \left(1 - \frac{15}{4\pi}\alpha_s\right) \qquad (9)$$

where

$$\frac{7}{4} g_q = \frac{7}{4}\ 2_s \times 2.5_f \times 3_c \left(1 - \frac{50}{21\pi}\alpha_s\right)$$

where the flavor degeneracy factor used is 2.5, allowing in a qualitative manner for the contribution of more massive strangeness.

The degeneracies of quarks and gluons were indicated by the subscripts s (spin) and c (color), respectively. One obtains (Letessier and Rafelski, 2004):

$$g_1 = \begin{cases} 56.5 & \text{for } \alpha_s = 0 \\ \approx 37 & \text{for } \alpha_s = 0.5 \\ \approx 33 & \text{for } \alpha_s = 0.6 \end{cases} \qquad (10)$$

In the present work, we have assumed the running coupling constant $\alpha_s(T)$ which is a function that depends on the temperature T, instead of the strong coupling α_s. The running coupling constant is taken as (Brau and Buisseret, 2007):

$$\alpha_s(T) = \frac{2\pi}{(11 - \frac{2}{3} n_f)\ \ell n(\frac{T}{\Lambda_\sigma})} \qquad (11)$$

where n_f is the number of quark flavors, (n_f = 0, 2, 3). From lattice QCD computations (Brau and Buisseret, 2007; Boyd, 1996), the parameters $\Lambda_\sigma = \beta$ T_c, where β = 0.104 $\pm$ 0.009 and the critical temperature, T_c, lies in the range of 150 to 300 MeV. In the present work, T_c is taken as T_c = 200 MeV.

THE QUARK-GLUON PLASMA (QGP)

One of the main activities in high-energy and nuclear physics is the search for the so-called quark-gluon plasma, a new state of matter which should have existed a few microseconds after the Big Bang. Just after the Big Bang, the universe was very hot and quarks were deconfined. As the universe cooled, the quark-gluon plasma disappeared in what may have been a deconfinement-confinement transition, but was more likely a smooth change rather than an abrupt transition. Today, neutron star cores are the most likely place to find a naturally occurring quark-gluon plasma. However, this plasma is cooler than in the early universe and it is made predominantly of matter, not an equal mixture of matter and antimatter (Gottlieb, 2007).

An early study has been done (Collins and Perry, 1975) to answer one of the important questions in perturbative QCD about the temperature dependence of the strong coupling constant, α_s (*T*). In the present work, the well-known one-loop expression for the running coupling constant has been used (Equation 11). This form is simpler than the two-loop expression and contains mainly the same physical information that α_s (*T*) decreases logarithmically as *T* increases. More rigorous treatments based on the renormalization group equations (RGE) were developed, with applications to perturbative QCD. Some of the calculations did not result in the logarithmical dependence of the coupling in the temperature (Steffens, 2006).

In general, the definition of a running coupling in QCD is not unique beyond the validity range of 2-loop perturbation theory. This is quite apparent when defining the coupling in QCD or in terms of the free energy potential (*T* = 0) (Kaczmarek et al., 2004).

RESULTS AND DISCUSSION

In the present work, we have considered the running coupling constant $\alpha_s(T)$ instead of the strong coupling constant α_s to calculate g_1, B, Δg and P_c.

In Figure 2, we calculated the selected form of the running coupling constant $\alpha_s(T)$ (Equation 11) versus temperature, T /T_c, and at different selected critical temperatures T_c = 150 and 200 MeV and at number of quark flavor n_f = 2. The solid curve represents the calculation of the running coupling constant $\alpha_s(T)$ at T_c =

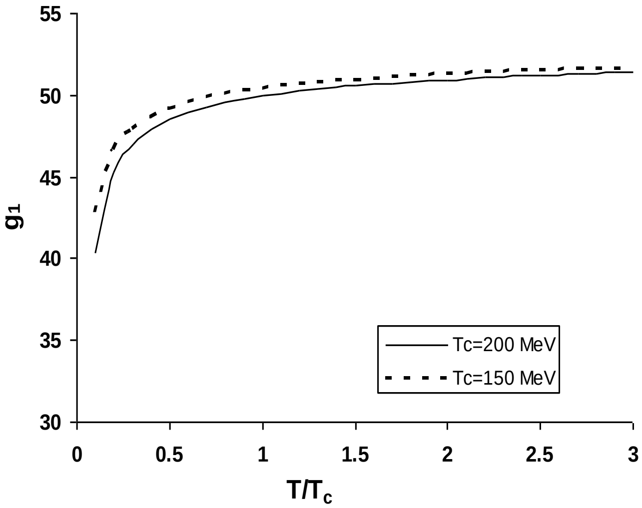

Figure 3. The degree of freedom in the deconfined QGP phase g_1 versus T/T_c.

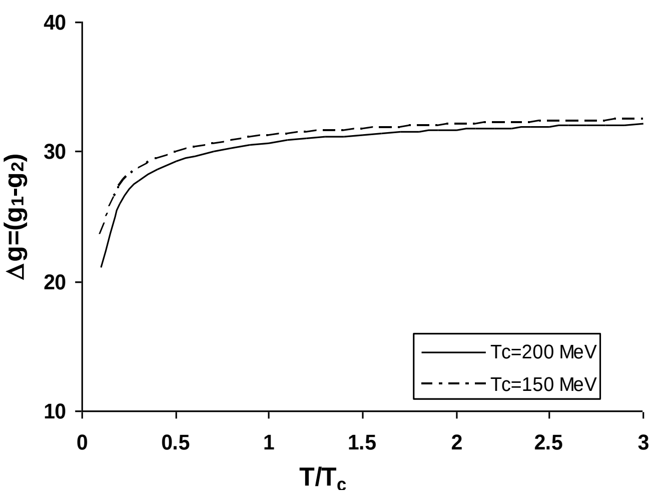

Figure 4. The difference between the deconfined and confined degrees of freedom Δg versus T/T_c.

200 MeV, and the dashed curve is the same plotting at T_c = 150 MeV. One can see that, the running coupling decreases logarithmically as *T* increases for different critical temperatures as well.

Figure 3 shows the behavior of the degree of freedom g_1 (Equation 8) in the deconfined QGP phase (Boyd 1996), within the temperature normalized to the critical one T_c = 150 and 200 MeV, where '1' refers to the primeval QGP phase. In this work, we inserted the running coupling constant $\alpha_s(T)$, which is a function of the temperature instead of a constant value of the strong coupling constant α_s.

It is obvious that the effect of the temperature in this

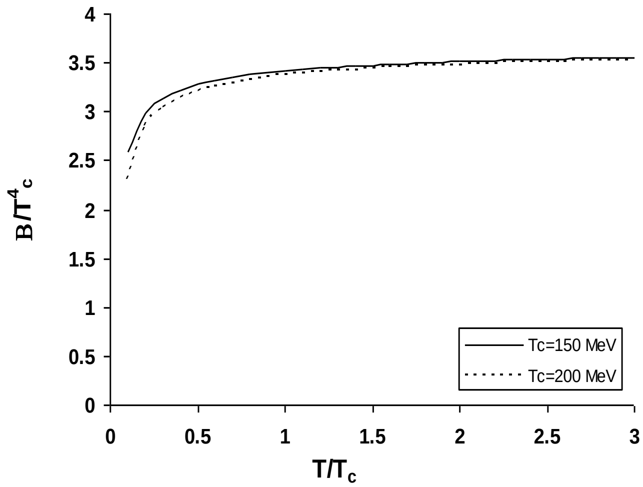

Figure 5. The latent heat between the confined and deconfined phase transition versus T/T_c.

formula according to the the running coupling constant (Equation 11). The change appears in g_g and g_q calculations, because of their dependence on α_s. The degree of freedom g_1 increases slightly with the temperature, and there is no qualitative change at different values of the critical temperature.

Figure 4 shows the difference between g_1 and g_2 (Δg) versus T/T_c in which g_1 is the effective one. Because of its dependence on the running coupling constant, whereas g_2 has constant value g_2 = 12.25. So far, we conclude that g_1 is the effective quantity in these calculations through the switch of the strong coupling constant to the running coupling constant.

Figure 5 shows the plot between the latent heat B/T_c^4 versus T/T_c at different values of critical temperatures T_c = 150 and 200 MeV. The solid curve is the calculation of B/T_c^4 at T_c = 200 MeV, and the dashed curve is the same calculation at T_c = 150 MeV. It is obvious that at T = T_c, the value of $B/T_c^4 \approx 3.2$.

Figure 6 is the most important curve according to the approach we used in this paper by inserting the running coupling constant $\alpha_s(T)$ instead of the strong coupling constant, α_s. This figure shows the relation between the critical pressure P_c/T_c^4 versus T/T_c at critical temperature T_c = 200 MeV. From this figure, one can determine the critical pressure, then at T = T_c, the value of $P_c/T_c^4 \approx 2.07$.

Then, one can calculate such curve at different values of T_c and determine the different critical values of the

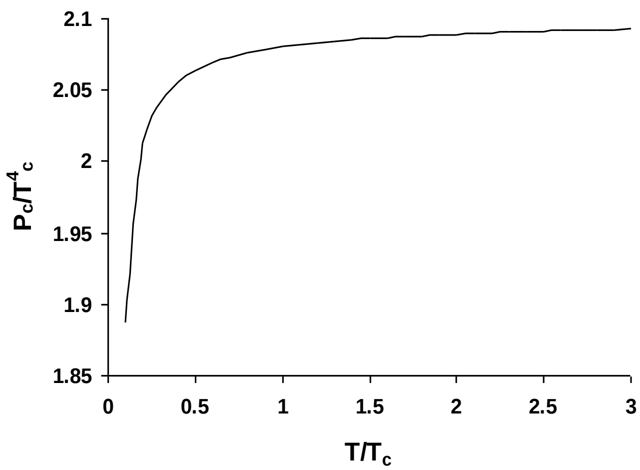

Figure 6. The critical pressure P_c/T_c^4 versus T/T_c, T_c = 200 MeV.

pressure. At this time, one has range of the critical pressure values according to the different value of T_c. This allows a wide range of temperature for this study. Also, from the computed curves at different critical temperature, one can expect the range which is convenient before deconfinement and the range after deconfinement. So, you can get a range for the phase transition point that can coincide.

Conclusion

In this work, we studied the effect of the running coupling constant instead of the strong coupling constant to calculate the degree of freedom, the latent heat and the critical pressure in the deconfined QGP phase of the early universe, the latent heat and the critical pressure. We concluded that, by inserting the running coupling constant in the calculations of the degree of freedom, the latent heat and the critical pressure at the transition temperature T_c, allow us to get a range for the critical pressure at different $T = T_c$.

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