BARYON CONTRAST RATIO IN AN ISENTROPIC COSMOLOGICAL
QUARK-HADRON PHASE TRANSITION

B.K.Patra and C.P.Singh

Department of Physics , Banaras Hindu University

Varanasi 221 005, India

ABSTRACT

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Assuming that the quark-hadron phase transition in the early Universe satisfies the Gibbs' construction for a first-order equilibrium phase transition with a further constraint of a continuous entropy per baryon-number ratio across the phase boundary, we show that the baryon contrast ratio R defined as a measure of the baryon-number density inhomogeneity across the phase interface, is independent of the critical temperature T_c for the phase transition. It does not depend on the QCD parameters as well. Our finding contradicts the earlier results.

I. INTRODUCTION

Quantum chromodynamics (QCD) predicts that a bulk piece of nuclear matter will undergo a phase transition when the temperature and/or the nuclear density are increased beyond certain critical value. We believe that such a QCD phase transition occurred at approximately 10^{-6} sec after the Big-Bang in the early Universe. Many aspects of the phase transition are still a matter of debate[1,2]. For example, it is not completely clear whether this phase transition was of a first-order or of a higher order. Although recent lattice calculations favour it being first-order for the realistic case of two degenerate light u and d quarks and a heavier s quark. Similarly the estimates for the critical temperature lie in the range of 100-200 MeV. Recently Witten[3] and then Applegate and Hogan[4] proposed that the early Universe witnessed a first-order quark-hadron phase transition which caused sufficient inhomogeneity in the baryon-number density during the separation of the cosmic phases. Consequently a large local fluctuation in the baryon to photon ratio could arise which might subsequently modify the standard picture of the primordial nucleosynthesis(PNS). Such a fluctuation might also result into the formation of quark nuggets and/or quark stars etc., which thus could solve the outstanding cosmological problem of the dark matter. The magnitude of this fluctuation is estimated by the baryon contrast ratio R of the net baryon-number density in the quark-gluon plasma (QGP) phase to that in the hadron gas (HG) phase, i.e., $R = n_{\text{QGP}}^B / n_{\text{HG}}^B$ and this ratio R is

evaluated at the critical temperature T_c and the baryon chemical potential $\mu = 10^{-10} T_c$. If $R \gg 1$, we get a thermodynamically favourable condition for the baryon-number to reside predominantly in the QGP phase. The baryon density inhomogeneity arising due to such a quark-hadron phase transition will alter the yields of the primordial nucleosynthesis (PNS) which is a function of the baryon contrast ratio and the neutron to proton ratio (n/p) [5]. Here R depends on the critical temperature T_c and n/p ratio depends on the extent of the neutron diffusion and is thus a function of the fractional volume of high as well as low density phases and the mean distance between the high density blobs.

Recently several theoretical attempts have been made to determine the values of R . A crucial element in such attempts lies in the choice of the equation of state (EOS) for the QGP as well as HG. Consequently the values of R resulting from a first-order quark-hadron phase transition in the early Universe have been of paramount significance in constraining the EOS for both the phases separately. Mostly the authors have assumed QGP and HG as ideal thermodynamical gases of point-like particles, respectively. Turner found [13] that the value of R is larger than one for T_c below 150 MeV when many low-lying baryon states are included in the HG phase. Murugesan et al. [14] have obtained the value of R which is much larger than one when T_c is smaller than 125 MeV. However, later they have manipulated the value of R around 10 by adjusting the value of the bag constant and suitably changing the QCD scale parameter Λ and claimed that $R \sim 10$ is found to be

appropriate in explaining the primordial abundances of the light elements in the non-standard big-bang theory[11,12]. We have demonstrated in an earlier paper[15,28] the importance of the incorporation of a hard-core volume correction into the hadronic EOS and the inclusion of QCD interactions in the QGP EOS. We obtained a unique constraint that if T_c lies in the range $150 \text{ MeV} < T_c < 260 \text{ MeV}$, the value of R is far less than 10 but is always larger than one. Kapusta and Olive[16] have arrived at the same conclusion using mean field theory to parametrize the repulsive interactions among the hadrons in the hadronic EOS which usually yields an erroneous result[23] in the early Universe scenario where the net baryon density approaches to very small value.

In the above models, a phase transition between the QGP and HG is obtained by construction using the Gibbs' criteria for the phase equilibrium. However, within the framework of such models, the specific entropy per baryon S/n_B is found to be discontinuous across the phase boundary. The natural change of a state will be thermodynamically possible only if the entropy either increases or remains constant during the phase transition. In the standard construction of an equilibrium phase transition from a quark-gluon plasma into a hadron gas, constraints of the entropy and the baryon-number conservation across the phase boundary causes a dilution and then reheating of the system and thus the values of chemical potential μ and temperature T have to be changed during the hadronisation while still satisfying the Gibbs' criteria for the equilibrium phase transition. The conservation

of total entropy and baryon number adjusts the ratio of the plasma to hadronic volume along the critical curve where the values of T and μ are determined by the pressure equality. Alternatively Leonidov et al.[17] have recently suggested that the entropy per baryon S/n_B ratio can still be kept constant across the quark-hadron phase boundary without changing the values of T_c or μ_c by simply incorporating T and μ dependent bag constant in the QGP equation of state. Hence the QGP hadronizes in the above approach at a constant temperature and chemical potential. We have further modified the μ and T - dependence of the bag constant by incorporating the QCD perturbative corrections in the equation of state (EOS) for the QGP and then explored in detail the consequences of such a bag constant $B(\mu, T)$ on the properties of the deconfining phase transition[18]. The purpose of this paper is to calculate the effect of the above model on the baryon density contrast ratio R . One important point in our calculation is that even though the phase transition is of first-order, it takes place almost reversibly at $T \approx T_c$ (i.e., with negligible supercooling). The overall pressure does not depend on the values of f_v which can account for the sharing of volumes between the two phases and, therefore, entropy is conserved. However, this somehow conflicts with the intuitive notion regarding the release of a latent heat in a first-order phase transition. Such a latent heat converts a part of quarks and gluons into leptons and photons and thus for a reversible transition, the amount of particles produced is just adequate to provide an adiabatic expansion.

II. FORMULATION OF $B(\mu, T)$

In order to construct an isentropic, equilibrium phase transition from a QGP to a hadron gas at a fixed temperature T and chemical potential μ , we require the continuity of the entropy per baryon ratio S/n_B across the phase boundary and this implies that $(S/n_B)_{\text{QGP}} = (S/n_B)_{\text{HG}}$. Leonidov et al.[17] have shown that this requirement can easily be met if the bag constant appearing in the QGP equation of state (EOS) becomes dependent on temperature T and baryon chemical potential μ and is given by a functional form $B(\mu, T)$. Thus we get a continuity condition of the ratio S/n_B [17] :

$$\frac{s_Q - s_Q^{\text{cor}}}{n_Q - n_Q^{\text{cor}}} = \frac{s_H}{n_H} \quad (1)$$

where s_Q , n_Q and s_H , n_H represent the entropy and baryon-number densities in the QGP and the HG phases, respectively, whereas the correction factors $s_Q^{\text{cor}} (= \frac{\partial B(\mu, T)}{\partial T})$ and $n_Q^{\text{cor}} (= \frac{\partial B(\mu, T)}{\partial \mu})$ arise due to μ , T dependent bag pressure in the EOS for the QGP phase.

We can write the partition function for a grand canonical ensemble of QGP consisting of free and massless u, d quarks and gluons as follows :

$$\frac{T}{V} \ln Z_Q(\mu_q, T) = \frac{37}{90} \pi^2 T^4 + \mu_q^2 T^2 + \frac{1}{2\pi^2} \mu_q^4 - B(\mu, T) \quad (2)$$

where μ_q is the quark chemical potential and is related to the baryon chemical potential as $3\mu_q = \mu$. Similarly we can write the partition function for the HG phase consisting of massless pions and $N, \bar{N}$ with

mass m as given below :

$$\frac{T}{V} \ln Z_H(\mu, T) = \frac{\pi^2 T^4}{30} + \frac{4m^2 T^2}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n^3} K_2(nm/T) \cosh(n\mu/T) \quad (3)$$

where K_2 is the modified Bessel function of second kind and summation over n arises because of the use of the quantum statistics.

It has already been noticed[19] that in order to construct a sensible quark-hadron phase transition, we must incorporate bag constant in the EOS for the QGP and a repulsive hard-core baryonic interaction in the HG phase. The repulsive force has been considered in the literature either by giving a geometric hard-core volume to each baryon[20-24] or by the mean-field approach[25]. Cleymans et al.[20] have introduced a correction factor $1/(1+V_O n_B^O)$ by which all point-like thermodynamical quantities e.g. energy density, entropy density etc. are multiplied. Here n_B^O is the net-baryon density for the point-like baryons (i.e. $n_B^O = \frac{T}{V} \frac{\partial \ln Z}{\partial \mu}$) and V_O is the eigen-volume of a single nucleon. Thus the net baryon density of finite-size nucleons is

$$n_B = \frac{n_B^O}{1 + V_O n_B^O} \quad (4)$$

and similar multiplicative factor also appears for the entropy density. In the Kuono-Takagi model[21], incorporation of repulsive interactions between a pair of nucleons and a pair of antinucleons separately yields the net baryon density as :

$$n_B^{KT} = \frac{n_B^O}{1 + V_O n_B^O} - \frac{n_B^O}{1 + V_O n_B^O} \quad (5)$$

where $n_B^0(n_{\bar{B}}^0)$ is the baryon(anti-baryon) density for the point particles. We have taken $V_O \approx V_p = \frac{4}{3}\pi r_p^3$ where r_p is the hard-core radius of a proton and is taken as 0.8 fm. In the early Universe case, the temperature was very large and hence there were a large number of baryons as well as anti-baryons and pions, although the net baryon density was still very small. Thus the applicability of Kuono-Takagi model appears more relevant in this context.

Since the expression for the pressure always involves even functions in μ and T , the bag pressure $B(\mu, T)$ should be an even function of μ and T . Hence in the zeroth iteration for deriving $B(\mu, T)$, we have neglected $\frac{\partial B(\mu, T)}{\partial T}$ which is proportional to μ^2 in comparison to the term $\frac{\partial B(\mu, T)}{\partial \mu}$ which is linear in μ . So in the case of early Universe, as we have a very small value of chemical potential we can neglect $\frac{\partial B(\mu, T)}{\partial T}$. Moreover, in the low baryon density limit, we can retain the first term only in the series expansion involved in Eq.(3).

Finally Leonidov et al. obtained the expression for the T and μ dependent bag pressure $B(\mu, T)$ in the low baryon density limit as[17] :

$$B(\mu, T) \approx B_0 + \frac{1}{9} \mu^2 T^2 + \frac{\mu^4}{162\pi^2} - \frac{148}{3\pi^2} m^2 T^2 K_2(m/T) \left(\cosh(\mu/T) - 1 \right) \quad (6)$$

where B_0 is the usual bag constant which represents the non-perturbative vacuum pressure. It can also be noted that the functional form of the bag pressure $B(\mu, T)$ does not depend on the EOS used for HG phase in the low baryon density limit.

Recently we have demonstrated[18] that the $B(\mu, T)$ as given by Leonidov et al. does not give the correct μ and T behaviour in the high baryon density limit because we expect that the bag pressure $B(\mu, T)$ should always decrease with increasing μ and/or T . We found that the incorporation of the perturbative QCD interactions in the QGP equation of state yields an expression for $B(\mu, T)$ which cures the above anomalous behaviour. Including the QCD interactions upto the second-order[26] in strong coupling $g_s^2/4\pi$ (or α_s), we thus get a modified expression for the partition function in the QGP phase as follows :

$$\begin{aligned} \frac{T}{V} \ln Z_Q(\mu_q, T) = & \frac{37}{90} \pi^2 T^4 + \mu_q^2 T^2 + \frac{1}{2\pi^2} \mu_q^4 \\ & - \alpha_s(\mu_q, T) \left(\frac{11}{9} \pi T^4 + \frac{2}{\pi} \mu_q^2 T^2 + \frac{\mu_q^4}{\pi^3} \right) - B(\mu, T) \end{aligned} \quad (7)$$

where $\alpha_s(\mu_q, T)$ is the QCD running coupling constant and μ_q and T dependence of α_s for two massless flavours is given below[27] :

$$\alpha_s(\mu_q, T) = \frac{12\pi}{29} \left[\ln \left(0.8 \mu_q^2 + 15.622 T^2 \right) / \Lambda^2 \right]^{-1} \quad (8)$$

Here Λ is the scale fixing parameter in QCD.

Now we solve the differential Eq.(1) for the interacting QGP equation of state (Eq.(7)) using iteration method. We continue this iteration method to still higher orders until $(S/n_B)_Q = (S/n_B)_H$ condition is satisfied. After two steps of iteration, we get the final expression for $B(\mu, T)$ as follows (please see in ref.[18]) :

$$\begin{aligned}
B(\mu, T) = & B_0 + \frac{1}{9} \mu^2 T^2 + \frac{\mu^4}{162\pi^2} \\
& - \alpha_s(\mu, T) \left(\frac{11}{9} \pi T^4 + \frac{2}{9\pi} \mu^2 T^2 + \frac{\mu^4}{81\pi^3} \right) \\
& - \frac{148}{3\pi^2} m^2 T^2 K_2(m/T) \left[\cosh(\mu/T) - 1 \right]
\end{aligned} \tag{10}$$

We notice from Eq.(10) that our expression for $B(\mu, T)$ agrees with that of Leonidov et al.[17] when $\alpha_s(\mu, T)=0$. This occurs exactly what we anticipated. Thus, the Eq.(10) is useful to obtain an EOS for the QGP at a low value of the baryon density and at a large temperature.

It is obvious that if we substitute the expression for $B(\mu, T)$ either in Eq.(2) from Eq.(6) or in Eq.(7) from Eq.(10) with QCD perturbative interactions, we get the partition function for the QGP :

$$\frac{T}{V} \ln Z_Q(\mu, T) = \frac{37}{90} \pi^2 T^4 + \frac{148}{3\pi^2} m^2 T^2 K_2(m/T) \left[\cosh(\mu/T) - 1 \right] - B_0 \tag{11}$$

One can notice that the partition function for the QGP does not depend on α_s or Λ if we demand the continuity of S/n_B ratio across the phase boundary. This result contradicts the findings of Murugesan et al.[14] who have obtained a significant dependence of the baryon density contrast ratio R on α_s and/or Λ .

III. RESULTS AND DISCUSSIONS

In Fig.1 we have shown the variation of baryon density contrast ratio R with the critical temperature T_c for the value of the baryon chemical potential $\mu = 10^{-10} T_c$ which represents early Universe scenario. We find that by constructing an equilibrium phase transition with S/n_B

ratio continuous across the phase boundary, the value of R is independent of T_c if we use Cleymans-Suhonen model for the excluded volume correction in the HG equation of state in deriving the form for $B(\mu, T)$. Obviously this finding supports the following result :

$$R = \frac{n_B^{\text{QGP}}}{n_B^{\text{HG}}} = \frac{s^{\text{QGP}}}{s^{\text{HG}}} = \frac{37}{3}$$

Thus R has a constant value and is equal to 12.3 which is exactly the ratio of the degrees of freedom in the QGP to those in HG phase and hence is independent of the values of T_c . If we include nonstrange mesons (ρ , η , ω etc.) in our calculation, the value of R will obviously decrease because the entropy density s^{HG} increases. However, the decrease is still small because the of heavier mesons at a critical temperature lying in the range 100-150 MeV yield small contributions. In principle, one can also incorporate strange hadrons but the calculation will become rather involved(see ref.[29]). It can be noted that a phase transition at a given μ - T point corresponds to only one of the many possibilities. However, we obtain the value of R for other values of μ and T by shifting them along the critical line. It should also be emphasized that in the early Universe case the net baryon density n_B^0 is very small and hence $n_B^0 v_0 \ll 1$ in the Cleymans correction factor. However, if we use Kuono-Takagi model for the HG equation of state by including baryons and antibaryons, we find that the value of R remains constant upto $T_c=150$ MeV and after that it increases rapidly. This can be interpreted in terms of the decreasing value of n_B^{HG} as T_c

increases. The early Universe corresponds to a very small chemical potential. A natural question arises as how relevant a correction factor due to the excluded-volume effect is in this situation. As already pointed out by us, the temperature is very large in the case of early Universe, and hence a large number of baryons and anti-baryons are present, although the net baryon density is small. Therefore, Kuono-Takagi model is more useful in the early Universe situation for the incorporation of excluded-volume correction. Although it does not affect Eq.(10) for $B(\mu, T)$, but it alters the value of n_B^{HG} which enters the expression for R . We find that the continuity of the S/n_B ratio across the phase boundary alters the value of R by a significant amount. For comparison, we have also shown in Fig.1 the curves obtained for the contrast ratio R when the condition of the constant S/n_B ratio across the phase boundary is not satisfied but Gibbs' construction is used to determine the parameters of the equilibrium phase transition and the descriptions of the HG incorporating the hard-core repulsive interactions are achieved in the models of Cleymans-Suhonen[20] and Kuono-Takagi[21], respectively. We find significant qualitative as well as quantitative changes in the values of R .

Here one point may be mentioned that our above calculation of R assumes the universe which is in complete thermal and chemical equilibrium during the phase transition. But in reality, the cosmic first order phase transition will necessarily result in deviations from thermal and chemical equilibrium because the low temperature hadron phase is not nucleated immediately at T_c , since a generic feature of

quantum or thermal nucleation is that the nucleation rate does not become large until the temperature has dropped below the coexistence temperature T_c [8]. The magnitude of these deviations will depend on the efficiency of heat and baryon transport during the phase transition[9,10]. In this scenario, latent heat transport is by the motion of the boundary wall which converts volume from one vacuum to another. This vacuum energy difference can drive particle creation. However, the heat or entropy could be carried out across the phase boundary by neutrinos apart from the surface evaporation of the hadrons. Baryon-number is not thermally created in the hadron phase and thus must actually flow across the boundary by the strong interaction physics if the hadron gas phase is going to have any net baryon-number at all. There are two limits to the efficiency of baryon-number transport across the phase boundary. In first, the baryon-number is rapidly and efficiently transported across the front to achieve chemical equilibrium[6] and the other corresponds to an inefficient transport process in which chemical equilibrium is not necessarily achieved on the time scale of phase co-existence evolution. However, in both these cases isothermal baryon-number fluctuations will result[9]. Our calculation is in the limit of efficient baryon transport mechanism. In the second case, when the bubbles of QGP are small in size (i.e. towards the end of the phase transition) phase boundaries will move at high velocities. If the phase boundaries move rapidly compared to baryon transport rates, then the chemical equilibrium in baryon-number across the phase boundaries may break down and baryons

could be concentrated in the shrinking QGP bubbles[30]. In such a situation, the magnitude of the resulting baryon-number fluctuation at the time of phase decoupling will again be given by the baryon contrast ratio R but now each of the two phases will have a different baryon chemical potential. Thus this ratio will obviously be larger than the equilibrium ratio. Therefore, the magnitude of isothermal baryon-number fluctuations generated in the case of chemical equilibrium corresponds to the lower limit when the actual baryon-number transport processes are considered[9].

In conclusion, the incorporation of hard-core volumes for the baryons in the HG and treating a QGP as weakly interacting plasma substantially change the values of the parameters of the phase transition and these corrections are, in fact, essential for a realistic description of the quark-hadron phase transition. In addition to the above corrections, we consider here the entropy and baryon-number conservation across the quark-hadron phase boundary existing in the case of early Universe to complete the phase transition reversibly at almost constant T_c and μ_c by introducing a phenomenological T and μ bag constant $B(\mu, T)$, instead of conventional bag model approach. The continuity of S/n_p ratio across the quark-hadron phase boundary modifies the value of R and we get $R \approx 12.3$ for the physical values of the critical temperature $T_c < 200$ MeV. This implies that the ignorance of the exact value of T_c of the phase transition will not lead to any kind of uncertainty in the prediction of R . Moreover, R does not depend on the QCD parameters like strong

interaction coupling constant α_s and /or the scale parameter Λ and hence the presence of interaction in the EOS for a QGP does not change the values of R which signifies the result of our calculation. It thus contradicts the findings of Murugesan et al.[14]. Furthermore, the constancy of the value of R around $R=12$ implies that the isothermal baryon-number fluctuation arising in the isentropic, equilibrium quark-hadron phase transition which occurred in the early Universe would almost have a constant value. However, this fluctuation could be modified at a later epoch by a diffusive separation of neutrons and protons. However, synthesis of ^4He , ^2H and ^3He appears consistent within the observational constraints and is independent of the size of the fluctuation for $R>20$ [20] for $\Omega_b=1$ baryons. But ^7Li appears to be overproduced in both the neutron and proton rich phases. This paper throws considerable light on the modification of the EOS of a QGP. Its effect on the yields of the primordial nucleosynthesis should carefully be investigated in details in the further studies.

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FIGURE CAPTION

Fig.1 The variation of the baryon density contrast ratio R with T_c . Curve A represents the calculation when hadron gas is described in Cleymans-Suhonen model and the EOS of QGP has a temperature and baryon chemical potential-dependent bag pressure. Curve D shows the results of calculation with HG in Kuono-Takagi model with T and μ dependent bag constant in the EOS of QGP.