

Baryon inhomogeneities due to CP violating QCD $Z(3)$ walls

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Abstract. We have investigated the possibility of generating baryon inhomogeneities in the quark-gluon plasma phase in the early universe due to CP violating scattering of quarks and anti-quarks from moving $Z(3)$ domain walls. CP violation, here, is spontaneous in nature, and arises from the non-trivial profile of the background gauge field between different $Z(3)$ vacua. We have calculated the spatial variation of the background gauge field across the $Z(3)$ interface from the profile of the Polyakov loop $L(x)$ for the $Z(3)$ interface and determined the reflection coefficients of quarks and anti-quarks using the Dirac equation. Our results have shown that the reflection coefficients of quarks and anti-quarks can differ by a large amount. We have discussed the implications of this for baryon inhomogeneity generation from collapsing large $Z(3)$ walls.

1. Introduction

Our Universe has gone various phase transitions throughout its expansion history. One such transition is confinement-deconfinement phase transition that is supposed to have occurred when universe had cooled to around $T = 200 \text{ MeV}$. The order parameter for confinement-deconfinement phase transition is Polyakov loop, and defined as:

$$L(x) = \frac{1}{N} \text{Tr} \left[\mathbf{P} \exp \left(ig \int_0^\beta A_0(\vec{x}, \tau) d\tau \right) \right]. \quad (1)$$

In confining phase, $\langle L(x) \rangle = 0$, while $\langle L(x) \rangle \neq 0$ in deconfined phase. Under $Z(N)$, which is centre of $SU(N)$, $L(\vec{x}) \longrightarrow e^{i\phi} \times L(\vec{x})$, where $\phi = 2\pi m/N$, and $m = 0, 1, \dots, (N-1)$. This leads to N -fold (for QCD, $N = 3$) degeneracy of ground states in deconfined state. As a result, domains with different $L(\vec{x})$ values will form and interfaces will exist between different domains. Note that in the presence of quarks, Polyakov loop is not an exact order parameter. So, we have worked with only pure QCD. Also, from now on, we have used $L(\vec{x})$ in place of $\langle L(x) \rangle$ for brevity.

An effective potential for Polyakov loop, as given by Pisarski [1] is:

$$V(L) = \left(-\frac{b_2}{2} |L|^2 - \frac{b_3}{6} (L^3 + (L^*)^3) + \frac{1}{4} (|L|^2)^2 \right) b_4 T^4. \quad (2)$$

For $T > T_c$, second term leads to the three degenerate vacua. Parameters b_2, b_3 and b_4 are fixed using lattice results [2, 3, 4].



2. CP violating quark scattering from $Z(3)$ walls

The scattering of quarks from these $Z(3)$ walls has been studied in [5]. There, the profile of $L(\vec{x})$ was calculated (Figure 1 (a)) by energy minimization and quark scattering along with its cosmological implications was discussed. However, in [5], no CP violation is present as $L(\vec{x})$ couples with q, \bar{q} in an identical manner.

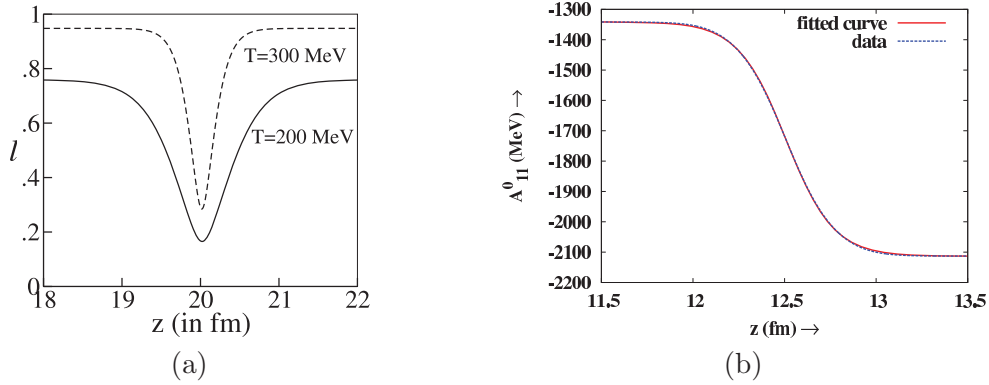


Figure 1. (a) $L(\vec{x})$ profile. (b) A_0 profile. Only (1, 1) component is shown.

2.1. Background A_0 profile

In [6], exact background profile was calculated by making the gauge choice given as:

$$A_0 = \frac{2\pi T}{g} (a\lambda_3 + b\lambda_8), \quad (3)$$

where a and b are constants, λ_3 and λ_8 are Gell-Mann matrices. Eq. (3) is then inserted in Eq. (1), and solved numerically for the profile given by the Figure 1 (a) to get the background A_0 (Figure 1 (b)). Reflection coefficients were calculated and it was also shown that CP violation is stronger for heavier quarks. The origin of CP violation is spontaneous in nature. (See [6] for detailed discussion on this aspect.)

3. Generation and evolution of baryon inhomogeneities

3.1. Physical picture

After inflation, the universe starts reheating and eventually the temperature is higher than critical temperature for confinement-deconfined transition. At this stage, the universe is in deconfined state and as a result, a network of $Z(N)$ interfaces is formed. The exact details of the formation of these networks itself makes an engrossing study, and is not very clear. However, one may expect it to depend on the details of reheating itself. For example, whether universe slowly reheats above the T_c or whether it quenches to a temperature above T_c may be one of the important factors in determining the network of these interfaces.

After reheating, the formation of $Z(3)$ domains is by Kibble mechanism. For $T \gg \Lambda_{QCD}$, the energy scale for these walls is set by the temperature of the universe. However, in the presence of quarks, there is a pressure difference between the true vacuum and the meta-stable vacua [7, 8]. This leads to a preferential shrinking of meta-stable vacua. As the collapse of these regions can be very fast (simulations indicate $v_w \sim 1$ [9, 10]), these can survive upto QCD phase transition only in low energy inflation models. However, there is a possibility that when effects of friction experienced by domain wall are taken into account their collapse may be slower. In that case, one may do away with the requirement of low energy inflation. (For a detailed discussion of

these aspects see [5].) In such a scenario, due to CP violating effects, q and \bar{q} scatter differently, and this results in the segregation of baryon number.

3.2. Evolution of inhomogeneities

While studying the evolution of these inhomogeneities, we have assumed constant temperature. This is possible if we ignore the effects coming from the reheating due to decreasing surface area as the wall collapses. This also allows us to ignore the expansion of the universe. This is consistent with the very fast moving domain walls as they collapse in time smaller than the Hubble time.

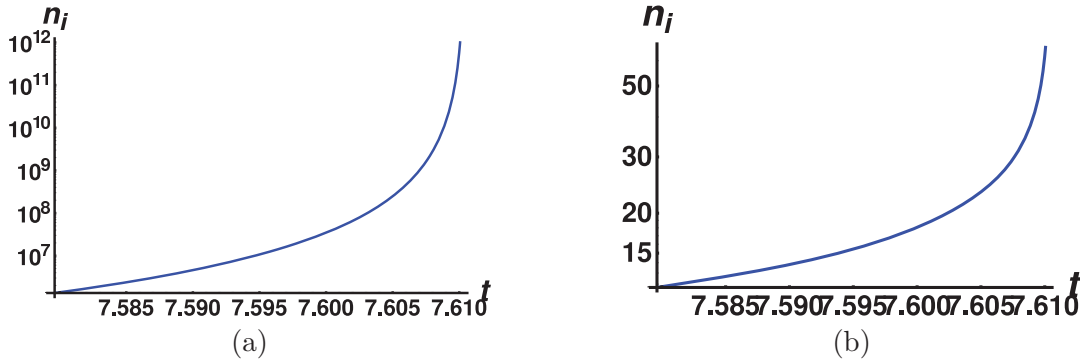


Figure 2. Number density evolution: (a) For charm-quark, and (b) For anti-charm.

The equations for studying quark number density concentration inside and outside the domain wall are [5] given by:

$$\dot{n}_i = \left(-\frac{2}{3}v_w T_w n_i + \frac{n_o T_- - n_i T_+}{6} \right) \frac{S}{V_i} - n_i \frac{\dot{V}_i}{V_i}, \quad \text{and} \quad (4)$$

$$\dot{n}_0 = \left(-\frac{2}{3}v_w T_w n_i - \frac{n_o T_- - n_i T_+}{6} \right) \frac{S}{V_i} + n_o \frac{\dot{V}_i}{V_o}. \quad (5)$$

The above equations are simultaneously solved to get the number densities. Figures 2 (a) and 2 (b) show the evolution of number densities for charm-quark and anti-quark inside the collapsing domain wall at $T = 400 \text{ MeV}$. The domain wall is approximated by the step potential.

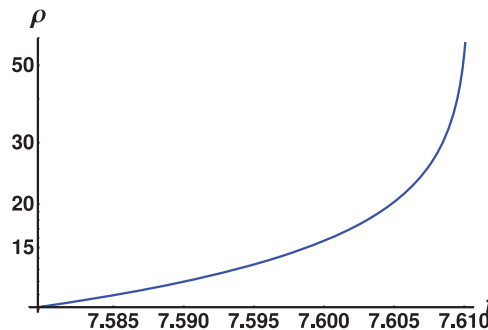


Figure 3. Evolution of baryon density profile.

It is clear that the number of quarks contained in the domain wall is several orders of magnitude higher than the number of anti-quarks. As the wall collapses, it leaves a profile of baryon density behind it. For a collapsing spherical wall, the baryon density at position R from the centre of the wall is given by [5]:

$$\rho(R) = \frac{\dot{N}_i}{4\pi v_w R^2}. \quad (6)$$

Figure 3 shows the density profile of charm anti-quark. As the quarks are completely reflected, they do not leave any density profile behind. It is important to note that Eqs. (4) and (5) assume that baryons homogenize in the two regions, while Eq. (6) does not take into account the diffusion of baryons through the wall.

4. Implications

It has been argued that the baryon inhomogeneities of sufficient initial magnitude will survive until nucleosynthesis [11]. This in turn can effect the nuclear abundances. Moreover, as these inhomogeneities are produced above quark hadron phase transition, they may alter the dynamics of phase transition [12].

These shrinking domain walls have a net baryon number concentrated in them, that can lead to the formation of stable baryonic lumps called *quark nuggets* [13]. Also, the inhomogeneities that are produced above electro-weak phase transition will change the standard baryogenesis scenario.

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