Nuggets Anti-Nuggets Formation from QCD $Z(3)$ Domains

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We investigate the possibility of segregation of baryons and anti-baryons in the quark-gluon plasma phase in the early universe due to CP violating scattering of quarks and antiquarks from moving $Z(3)$ domain walls. CP violation here is spontaneous in nature and arises from the nontrivial profile of the background gauge field ($A_0$) between different $Z(3)$ vacua. We study the effect of this spontaneous CP violation on the baryon transport across the collapsing large $Z(3)$ domain walls (which can arise in the context of certain low energy scale inflationary models). Our results show that this CP violation will lead to the segregation of baryons and anti-baryons in early universe near the confinement-deconfinement phase tranition epoch. We discuss consequences of this baryon anti baryon segregation in the subsequent cosmological evolution.

Key Words : Early Universe; CP Violation; Phase Transition

Introduction

Our universe has undergone various phase transitions throughout it’s expansion history. One such transition is confinement-deconfinement phase transition that is supposed to have occurred when universe had cooled to around $T = 200\, MeV$. Witten (1984) proposed that if universe underwent a first order QCD phase transition, then the bubbles of high temperature phase would shrink, in the process trapping the baryons inside them. Since then, it has been argued that these quarks nuggets can be stable and survive up to the present epoch (Bhattacharjee et al., 1993; Lugones and Horvath, 2004; Bhattacharyya et al., 2002). These nuggets can provide a viable dark matter candidate within the standard model of particle physics. However, lattice QCD calculations have ruled out the first order phase transition and hence the mechanism of formation of quark nuggets as proposed by Witten doesn’t hold. In Witten’s scenario, the importance of first order...
phase transition was due to the fact that it provides us with an interface between two region of the universe. The baryon transport across the phase boundary then leads to the build up of baryon excess in the collapsing domains. That is not achieved in a crossover or a second order phase transition. Nonetheless, these exciting objects have since then fascinated cosmologists and even now there are attempts to detect these objects (Gorham, 2012; Astone et al., 2013).

\[ Z(3) \] interfaces provide us with an attractive alternative to the phase boundary. These interfaces arise from the spontaneous breaking of \( Z(3) \) symmetry in the high temperature phase (QGP phase) of QCD. In this work we consider a scenario where not only nuggets but also anti-nuggets can be formed by these collapsing QCD \( Z(3) \) walls. The order parameter for confinement-deconfinement phase transition is Polyakov loop, defined as

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

In confining phase, \( \langle L(x) \rangle = 0 \), while \( \langle L(x) \rangle \neq 0 \) in deconfined phase. Under \( Z(N) \), which is center of \( SU(N) \), \( L(\vec{x}) \rightarrow e^{i\phi} \times L(\vec{x}) \), where \( \phi = 2\pi m/N; m = 0, 1,...(N-1) \). 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 presence of quarks Polyakov Loop is not an exact order parameter. So, we will work with only pure QCD.

An effective potential for Polyakov Loop as given by Pisarski (Pisarski, 2000) is

\[
V(L) = \left( -\frac{b_2}{2} |L|^2 - \frac{b_3}{6} \left( L^3 + (L^*)^3 \right) + \frac{1}{4} (|L|^2)^2 \right) b_4 T^4.
\] (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 (Dumitru and Pisarski, 2001, 2002).

**CP Violating Quark Scattering from \( Z(3) \) Walls**

Quark nuggets formation from collapsing \( Z(3) \) walls was studied in (Layek et al., 2006). There, the quark scattering was from \( L(\vec{x}) \) profile (Fig. 1A). As \( L(\vec{x}) \) couples with \( q, \bar{q} \) in an identical manner, there was no CP violation. CP violation was first discussed in (Korthals Altes and Watson, 1995; Korthals Altes et al., 1994), in context of baryogenesis.

In (Atreya et al., 2012), exact background profile was calculated by making the gauge choice

\[
A_0 = \frac{2\pi T}{g} \left( a\lambda_3 + b\lambda_8 \right),
\] (3)

where \( a \) and \( b \) are constants, \( \lambda_3 \) and \( \lambda_8 \) are Gell-Mann Matrices. Eq. (3) is then inserted in eq. (1) and solved numerically for the profile given by Fig. a to get the background \( A_0 \) (Fig. 1B). 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 (Atreya et al., 2012) for detailed discussion on this aspect.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{(A) $L(z)$ profile. (B) $A_0$ profile. Only (1, 1) component is shown.}
\end{figure}

Generation and Evolution of Baryon Inhomogeneities

Physical Picture

After inflation, the universe reheats and eventually the temperature is higher than critical temperature for confinement-deconfinement transition. After reheating, the formation of $Z(3)$ domains is by Kibble mechanism. The exact details of the formation of these networks 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 $T_c$ could be one of the important factors in determining the network of these interfaces.

For $T >> \Lambda_{QCD}$, the energy scale for these walls is set by the temperature of the universe. However, in presence of quarks, there is a pressure difference between the true vaccum and the metastable vacua (Dixit and Ogilvie, 1991; Korthals Altes and Watson, 1995). This leads to a preferential shrinking of metastable vacua. As the collapse of these regions can be very fast (simulations indicate $v_w \sim 1$ (Gupta et al., 2010, 2012)), 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 (Chudnovsky and Vilenkin, 1988; Martins and Shellard, 1996). In that case, one may do away with the requirement of low energy inflation. For a detailed discussion of these aspects see ref. (Layek et al., 2006).
In such a scenario, due to CP violating effects, $q$ and $\bar{q}$ scatter differently and this results in the segregation of baryon number.

**Evolution of Inhomogeneities**

While studying the evolution of these inhomogeneities, we ignore the expansion of the universe. This is possible if the collapse of the domains is in much smaller time than the Hubble time. This allows us to ignore the change in temperature due to expansion. We also ignore the heating effects coming from the decreasing surface area as the wall collapses. This allows us to keep the wall height constant. The equations for studying quark number density concentration inside and outside the domain wall are

\[
\dot{n}_i = \left( -\frac{2}{3} v_w T_w n_i + \frac{v_{rel}^i n_o T_- - v_{rel}^i n_i T_+}{6} \right) \frac{S}{V_i} - n_i \frac{\dot{V}_i}{V_i},
\]

\[
\dot{n}_o = \left( -\frac{2}{3} v_w T_w n_i - \frac{v_{rel}^o n_o T_- - v_{rel}^o n_i T_+}{6} \right) \frac{S}{V_i} + n_o \frac{\dot{V}_i}{V_o},
\]

where $S$ is the surface area of the collapsing wall. $T_w$ is the transmission coefficient for the quarks inside the domain and moving parallel to the wall. The relative velocity for such quarks with respect to the wall is $v_w$, and they constitute $4/6$ of the total number of the inside quarks. $T_-$ ($T_+$) is the transmission coefficient calculated for the quarks that are moving from outside (inside) of the wall towards the inside (outside) with the relative velocity $v_{rel}^o$ ($v_{rel}^i$) with respect to the wall. Each contributes towards $1/6$ of the corresponding number densities. The above equations are simultaneously solved to get the number densities. Fig. 2(A) and (B) show the evolution of number densities for charm quark and anti-quark inside the collapsing domain wall at $T = 400 \text{MeV}$.

![Fig. 2: Number density evolution: (A) For charm-quark. (B) For anti-charm at T=400 MeV](image-url)
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 center of the wall is given by

$$\rho(R) = \frac{N_i}{4\pi v_w R^2}.$$  \hspace{1cm} (6)

Fig. 3 shows the density profile of charm quark. It is important to note that eq. (4) and eq. (5) assume that baryons homogenize in the two regions, while (6) does not take into account the diffusion of baryons through the wall. In this case, the baryon concentration was due to the interface between $l(x) = 1$ and $l(x) = z^2$ vacua. Interface between $l(x) = 1$ and $l(x) = z$ vacua, will trap anti-baryons as it is the conjugate of the wall between $l(x) = 1$ and $l(x) = z^2$. This leads to the formation of nuggets as well as anti-nuggets.

**Implications**

It has been argued that the baryon inhomogeneities of sufficient initial magnitude will survive until nucleosynthesis (ref. (Jedamzik and Fuller, 1994)). This in turn can affect the nuclear abundances. Moreover, as these inhomogeneities are produced above quark hadron phase transition, they may alter the dynamics of phase transition (Sanyal, 2003).

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 (Witten, 1984). These quark nuggets can act as
the seed to black hole formation (Lai and Xu, 2010). Also the inhomogeneities that are produced above electro-weak phase transition will change the standard baryogenesis scenario.

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References