Proc Indian Natn Sci Acad **81** No. 1 February 2015 Special Issue, pp. 237-243
© *Printed in India*. DOI: 10.16943/ptinsa/2015/v81i1/48076

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

ABHISHEK ATREYA*[1], ANJISHNU SARKAR[2] and AJIT M SRIVASTAVA[1]

[1]*Institute of Physics, Bhubaneswar*, 751 005, *India*
[2]*LNMIIT, Jaipur* 302 031, *India*

(Received on 29 April 2014; Accepted on 11 August 2014)

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 occured 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 upto 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 dosen't hold. In Witten's scenario, the importance of first order

Author for Correspondence : E-mail: atreya@iopb.res.in

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

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

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 $SU(N)$, $L(\vec{x}) \longrightarrow e^{i\phi} \times L(\vec{x})$, 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

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

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

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

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 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.

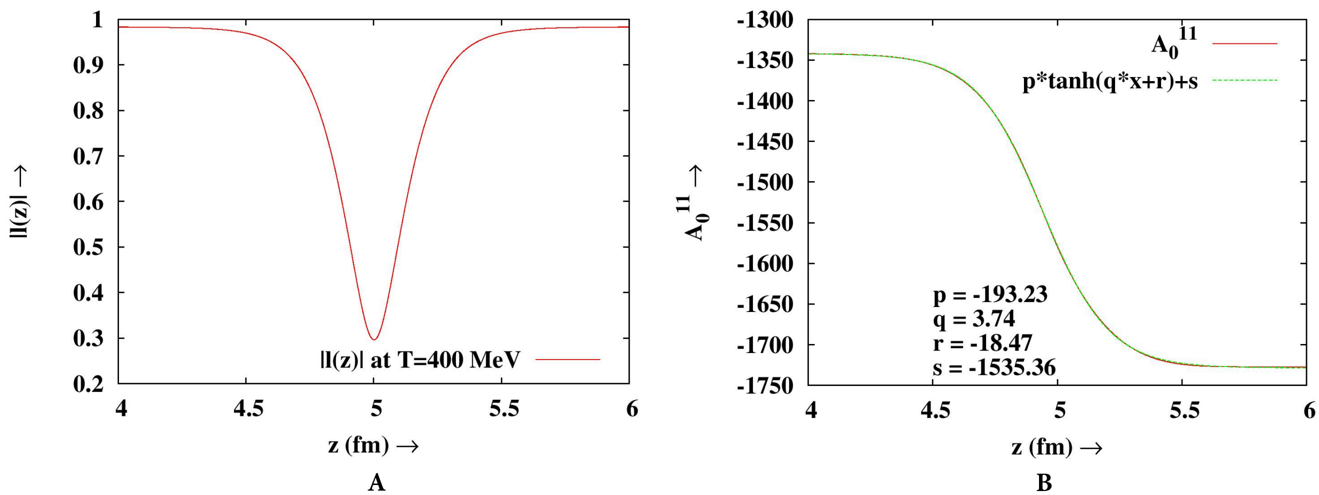


Fig. 1: (A) $L(\vec{x})$ profile. (B) A_0 profile. Only (1, 1) component is shown

Generation and Evolution of Baryon Inhomogeneites

Physical Picture

After inflation, the universe reheats and eventually the temperature is higher than critical temperature for confinement-deconfined 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.

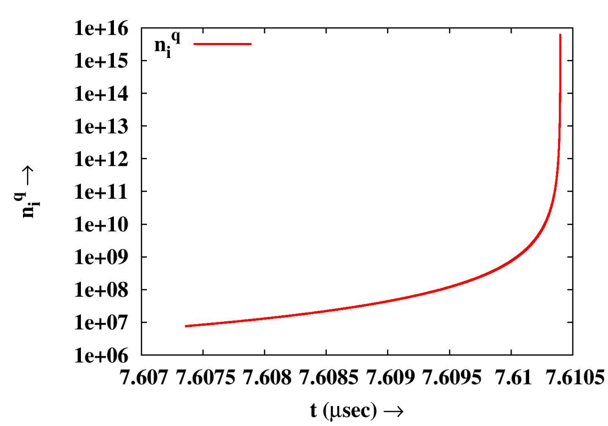
Evolution of Inhomogeneites

While studying the evolution of these inhomogeneites, 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

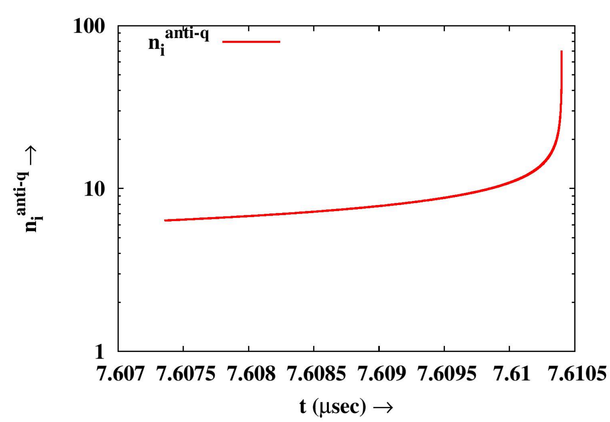
$$\dot{n_i} = \left(-\frac{2}{3}v_w T_w n_i + \frac{v_o^{rel} n_o T_- - v_i^{rel} n_i T_+}{6}\right)\frac{S}{V_i} - n_i\frac{\dot{V_i}}{V_i} \tag{4}$$

$$\dot{n_0} = \left(-\frac{2}{3}v_w T_w n_i - \frac{v_o^{rel} n_o T_- - v_i^{rel} n_i T_+}{6}\right)\frac{S}{V_i} + n_o\frac{\dot{V_i}}{V_o}, \tag{5}$$

where S is the surface area of the collapsing wall. T_w is the transmission coeffecient 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 coeffecient calculated for the quarks that are moving from outside (inside) of the wall towards the inside (outside) with the relative velocity v_o^{rel} (v_i^{rel}) with respect to the wall. Each contributes towards $1/6$ of the corresponding number desities. 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 $T = 400MeV$.



A



B

Fig. 2: Number density evolution: (A) For charm-quark. (B) For anti-charm at T=400 MeV

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

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

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 $l(x) = z^2$ vaccua. Interface between $l(x) = 1$ and $l(x) = z$ vaccua, 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.

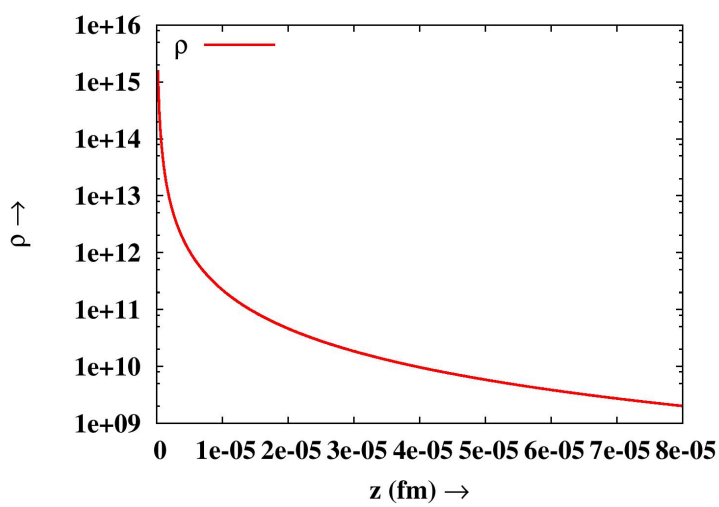


Fig. 3: Evolution of baryon density profile

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 inhomogeneties that are produced above electro-weak phase transition will change the standard baryogenesis scenario.

Acknowledgements

We thank Sanatan Digal, Saumia P. S., Partha Bagchi, and Ranjita Mohapatra for very valuable comments and useful discussions.

References

1. Astone P, Bassan M, Coccia E, D'Antonio S, Fafone V *et al*. (2013) Quark nuggets search using 2350 Kg gravitational waves aluminum bar detectors *astro-ph/1306.5164*
2. Atreya A, Srivastava AM and Sarkar A (2012) Spontaneous CP violation in quark scattering from QCD Z(3) interfaces *Phys Rev* **D85** 014009
3. Bhattacharjee P, Alam J, Sinha B and Raha S (1993) Survivability of cosmological quark nuggets in the chromoelectric flux tube fission model of baryon evaporation *Phys Rev* **D48** 4630
4. Bhattacharyya A, Banerjee S, Ghosh SK, Raha S, Sinha B, H Toki (2002) QCD chromodynamics phase transition in the early universe and quark nuggets *Pramana* **60** 909
5. Chudnovsky E and Vilenkin A (1988) Strings in the Sun? *Phys Rev Lett* **61** 1043
6. Dixit V and Ogilvie MC (1991) Metastability in SU(N) gauge theories at high temperatures *Phys Lett* **B269** 353
7. Dumitru A and Pisarski R D (2001) Event-by-event fluctuations from decay of a condensate for Z(3) Wilson lines *Phys Lett* **B504** 282
8. Dumitru A and Pisarski RD (2002) Two-point functions for SU(3) Polyakov loops near T(c) *Phys Rev* **D66** 096003
9. Gorham PW (2012) Antiquark nuggets as dark matter: New constraints and detection prospects *Phys Rev* **D86** 123005
10. Gupta US, Mohapatra RK, Srivastava AM and Tiwari VK (2010) Simulation of Z(3) walls and string production via bubble nucleation in a quark-hadron transition *Phys Rev* **D82** 074020
11. Gupta US, Mohapatra RK, Srivastava AM and Tiwari VK (2012) Effects of Quarks on the Formation and Evolution of Z(3) Walls and Strings in Relativistic Heavy-Ion Collisions *Phys Rev* **D86** 125016
12. Jedamzik K and Fuller GM (1994) The Evolution of nonlinear subhorizon scale entropy fluctuations in the early universe *Astrophys J* **423** 33
13. Korthals Altes CP and Watson NJ (1995) Hot standard model, metastable states and CP violation *Phys Rev Lett* **75** 2799.
14. Korthals Altes CP, Lee K and Pisarski RD (1994) Phase of the Wilson line at high temperature in the standard model *Phys Rev Lett* **73** 1754
15. Lai XY and Xu RX (2010) Formation of the seed black holes: a role of quark nuggets? *JCAP* **1005** 028

16. Layek B, Mishra AP, Srivastava AM and Tiwari VK (2006) Baryon inhomogeneity generation in the quark-gluon plasma phase *Phys Rev* **D73** 103514
17. Lugones G and Horvath JE (2004) Primordial nuggets survival and QCD pairing *Phys Rev* **D69** 063509
18. Martins CJAP and Shellard EPS (1996) String evolution with friction *Phys Rev* **D53** 575
19. Pisarski RD (2000) Quark-gluon plasma as a condensate of SU(3) Wilson lines *Phys Rev* **D62** 111501
20. Sanyal S (2003) Effect of pre-existing baryon inhomogeneities on the dynamics of quark hadron transition *Phys Rev* **D67** 074009
21. Witten W (1984) Cosmic Separation of Phases *Phys Rev* **D30** 272.