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Reviving Quark Nuggets as Dark Matter Candidates

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We discuss a novel mechanism for segregation of baryons and anti-baryons in the quark-gluon plasma phase which can lead to formation of quark and antiquark nuggets in the early universe, irrespective of the order of the quark-hadron phase transition. This happens 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 can lead to large concentrations of baryons and anti-baryons in the early universe. The quark and antiquark nuggets, formed by this alternate mechanism, can provide a viable dark matter candidate within standard model without violating any observational constraints.

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1. Introduction

One of the major mysteries in today's cosmological scenario is the form of dark matter. There are various models of dark matter, nearly all of them are non-baryonic in nature and motivated by scenarios that require physics beyond standard model. A common argument for the non-baryonic nature of dark matter is that the data on Nucleosynthesis and CMBR does not allow baryonic dark matter. That statement is not strictly correct as the constraints coming from CMBR and nucleosynthesis hold true for only for baryons in the form of gas (e.g. hydrogen, helium). These constraints are very strong on such forms of baryonic matter, restricting it to less than 20 % of all matter/radiation content of the universe (excluding the dark energy). These constraints do to apply if baryons are in the form of heavy, compact objects such as quark nuggets, MACHOS, etc. To avoid conflict with the data, such objects should form before nucleosynthesis. There are separate strong observational constraints on MACHOS from gravitational microlensing observations. On the other hand, quark nuggets pass through all the observational constraints, and indeed, these were considered promising dark matter candidates after the pioneering work of Witten [1]. He proposed that if universe underwent a first order QCD phase transition, then the bubbles of high temperature phase will 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[2, 3, 4]. 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 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 [5, 6]. In any case, it is hard to come up with scenarios where such heavy objects could form before nucleosynthesis.

In the deconfined phase of QCD (QGP phase), there are possibilities of extended topological objects. These are the QCD $Z(3)$ interfaces and they arise from the spontaneous breaking of $Z(3)$ symmetry in the high temperature 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. We restrict our discussion to pure glue theory. To study the confinement-deconfinement phase transition, the appropriate order parameter is Polyakov loop which is defined as

$$L(x) = \frac{1}{N} Tr\left[\mathbf{P}exp\left(ig\int_0^\beta A_0(\vec{x},\tau)d\tau\right)\right]. \tag{1.1}$$

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 $\phi = 2\pi m/N; m = 0, 1 \ldots (N-1)$. 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.

An effective potential for Polyakov Loop as given by Pisarski [7] is

$$V(L) = \left(-\frac{b_2}{2}|L|^2 - \frac{b_3}{6}\left(L^3 + (L^*)^3\right) + \frac{1}{4}(|L|^2)^2\right) b_4 T^4. \tag{1.2}$$

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 [8, 9]. The potential is used to calculate the $l(x)$ profile using energy minimization, see ref.[10] for details. Fig. (1) shows the plot of $|l(x)|$ for the interface between two different vacua at T = 400 MeV (in the absence of quarks all the three interfaces have same profile for $|l(x)|$).

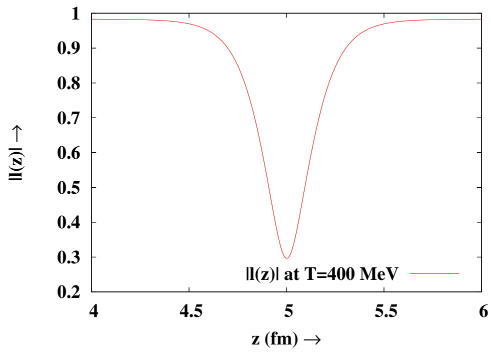


Figure 1: $L(\vec{x})$ profile for T = 400 MeV.

2. CP Violating Quark Scattering from $Z(3)$ Walls

Quark nuggets formation from collapsing $Z(3)$ walls was studied in [11]. There, the quark scattering was from $L(\vec{x})$ profile (fig. 1). As $L(\vec{x})$ couples with $q, \bar{q}$ in an identical manner, there was no CP violation. CP violation was first discussed in [12, 13], in context of baryogenesis. The

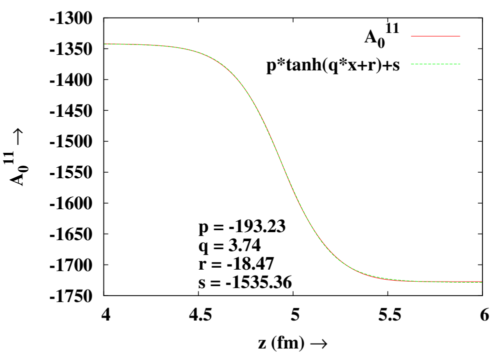


Figure 2: A_0 profile at T = 400 MeV. Only $(1,1)$ component is shown.

exact background profile was calculated in [14], by making the gauge choice

$$A_0 = \frac{2\pi T}{g}\left(a\lambda_3 + b\lambda_8\right), \tag{2.1}$$

where a and b are constants, λ_3 and λ_8 are Gell-Mann Matrices. Eq. (2.1) is then inserted in eq. (1.1) and solved numerically for the profile given by Fig. 1 to get the background A_0 (Fig.

2). 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 [14] for detailed discussion on this aspect.

3. Generation and Evolution of Baryon Inhomogeneites

3.1 Physical Picture

As these interfaces exist above the confinement transition temperature, these interfaces would be present in the pre inflationary era but during inflation these objects vanish as the universe cools. During reheating, when the temperature is higher than critical temperature for confinement-deconfined transition, these interfaces form by Kibble mechanism. The exact details of the formation of these networks is unclear. 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 the pure glue case all the vacua are degenerate, however in presence of quarks $Z(3)$ symmetry is spontaneously broken. This leads to a pressure difference between the true vaccum and the metastable vacua [15, 12]. As a result metastable vacua shrink preferentially. As the collapse of these regions can be very fast (simulations indicate $v_w \sim 1$ [16, 17]), these domains can survive upto QCD phase transition only in low energy inflation models. However, this constraint of low energy inflationary models can be possibly done away with when effects of friction experienced by domain wall are taken into account. It has been argued in literature that the particles hitting the wall can provide enough force so that collapse of domains may be a lot slower [18, 19]. For a detailed discussion of these aspects see ref. [11].

3.2 Evolution of Inhomogeneites

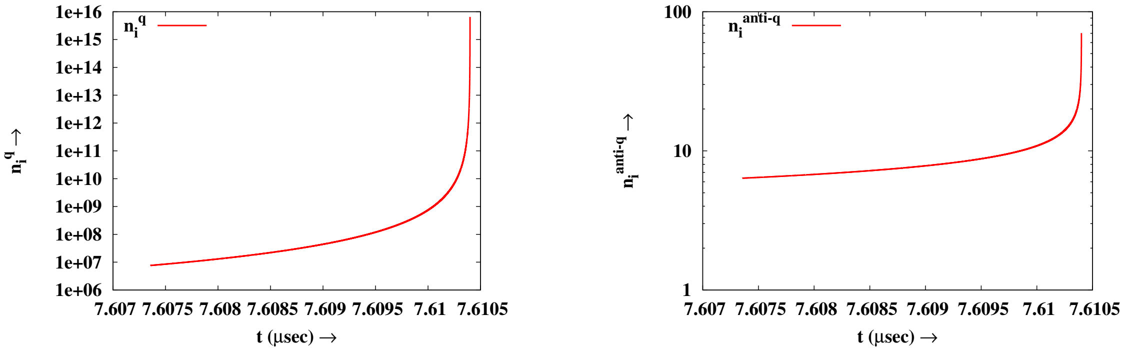
In scenario mentioned above, due to CP violating effects, q and $\bar{q}$ scatter differently and this results in the segregation of baryon number. This leads to an inhomogeneous distribution of baryons. We make certain approximations while studying the evolution of these inhomogeneites. We ignore the expansion of the universe. This is possible if the collapse of the domains is in much smaller time than the Hubble time. As a result we can ignore the change in temperature due to expansion. We also ignore the heating effects coming from the decreasing surface area as the wall collapses so that we can keep the height of the potential barrier constant. The equations for studying quark number density concentration inside and outside the domain wall are

$$\dot{n}_i = \left(-\frac{2}{3}v_w T_w n_i + \frac{v_o^{rel} n_o T_- - v_i^{rel} n_i T_+}{6}\right)\frac{S}{V_i} - n_i \frac{\dot{V}_i}{V_i} \tag{3.1}$$

$$\dot{n}_0 = \left(-\frac{2}{3}v_w T_w n_i - \frac{v_o^{rel} n_o T_- - v_i^{rel} n_i T_+}{6}\right)\frac{S}{V_i} + n_o \frac{\dot{V}_i}{V_o}, \tag{3.2}$$

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} $\left(v_i^{rel}\right)$ 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. 3(a) and 3(b) show the evolution of number densities for charm quark and anti-quark inside the collapsing domain wall at $T = 400 MeV$. It is



(a) (b)

Figure 3: Number density evolution: (a)For charm-quark. (b) For anti-charm at $T = 400\ MeV$

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

$$\rho(R) = \frac{\dot{N}_i}{4\pi v_w R^2}. \tag{3.3}$$

Fig. 4shows the density profile of charm quark. It is important to note that eq. (3.1) and eq. (3.2) assume that baryons homogenize in the two regions, while (3.3) 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 $l(x) = z$. This leads to the formation of nuggets as well as anti-nuggets.

4. Implications

It has been argued that the baryon inhomogeneities of sufficient initial magnitude will survive until nucleosynthesis (ref. [20]). 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 ([21]).

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 ([1]). These quark nuggets can act as the seed to black hole formation [22]. Also the inhomogeneties that are produced above electro-weak phase transition will change the standard baryogenesis scenario.

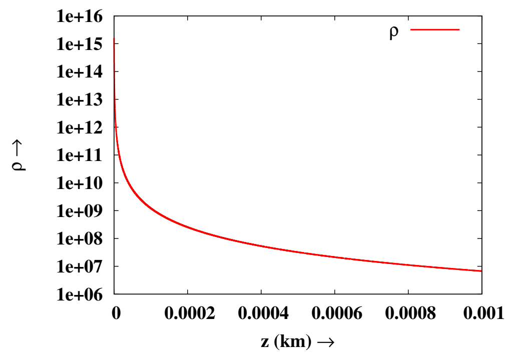


Figure 4: Evolution of baryon density profile.

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