Cosmological QCD Phase Transition and Dark Matter

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We calculate the size distribution of quark nuggets, which could be formed due to first order QCD phase transition in the early universe. We find that there are a large number of stable Quark Nuggets which could be a viable candidate for cosmological dark matter.

1 Introduction

A first order quark-hadron phase transition in the early universe at a critical temperature $T_c \sim 100-200$ MeV, lead to the formation of quark nuggets (QN), made of u, d and s quarks [1]. Under certain circumstances the primordial QN's will survive till the present epoch. The central theme of this work is the candidature of these quark nuggets as the baryonic component of the dark matter. This possibility leaves the results of big bang nucleosynthesis unaffected and does not invoke any exotic physics [2, 3, 4].

One of the significant issues in this context is the stability of these primordial QN's on a cosmological time scale. This question was first addressed by Alcock and Farhi [5] who argued that due to baryon evaporation from the surface, a QN, even with the largest possible baryon number, will not survive till the present epoch. Madsen *et al* [6] then pointed out that as the evaporation makes the surface of the nugget deficient in u and d quarks, further evaporation is suppressed. They came to a conclusion that QNs with initial baryon number $N_B \geq 10^{46}$ could well be stable against baryon evaporation. Later Bhattacharjee *et al* [7] found, using the chromoelectric flux tube model, that QN's with baryon number larger than 10^{42}, would survive against baryon evaporation.

In spite of these efforts, not much emphasis has been put towards the study of the size-distribution of the QNs. The size-distribution of the QNs is very important in the context of their candidature as dark matter as it tells us the most probable size of a QN. The calculation of the lower cut-off in size tells us the minimum size and the baryon number content of a QN that we should look for. We will carry out these studies in the cosmological QCD phase transition scenario.

2 The size-distribution of quark nuggets

The evolution of the cosmological scale factor during the quark-hadron phase transition epoch is given by,

$$R(t)/R(t_i) = (4r)^{1/3}\left[cos\left[\frac{3\,(t-t_i)}{2t_c\,(r-1)^{1/2}} + cos^{-1}\frac{1}{2r^{1/2}}\right]\right]^{2/3} \tag{1}$$

where $r = g_q/g_h$, $t_c = \sqrt{3m_{pl}^2/8\pi B}$, t_i is the time when phase transition starts and B is the bag constant. (For details and explanation of all the terms see ref. [8]).

In the coexisting phase, the temperature of the universe remains constant at T_c. In the usual picture of bubble nucleation in a first order phase transition scenario hadronic matter starts appearing as individual bubbles. With the progress of time, more and more hadronic bubbles form, coalesce and eventually percolate to form an infinite network of hadronic matter which traps the quark matter phase into finite domains. The time when the percolation takes place is usually referred to as the percolation time t_p, determined by a critical volume fraction f_c, ($f_c \equiv f(t_p)$) of the quark phase.

In an ideal first order phase transition, the fraction of the high temperature phase decreases from the critical value f_c, as these domains shrink. For the QCD phase transition, however, these domains should become QN's and as such, we may assume that the lifetime of the mixed phase $t_f \sim t_p$. The probability of finding such a domain of trapped quark matter of co-ordinate radius X at time t_p with nucleation rate $I(t)$ is given by [9],

$$P(X,t_p) = \exp\left[-\frac{4\pi}{3}\int_{t_i}^{t_p} dt I(t) R^3(t)\,(X + X(t_p,t))^3\right] \tag{2}$$

where $X(t_p;t)$ is the coordinate radius of a bubble, at time t_p, which nucleated at time t.

For convenience, we define a new set of variables $z = XR(t_i)/vt_c$, $x = t/t_c$ and $r(x) = R(x)/R(x_i)$; v is the radial growth velocity of a bubble. Then

$$P(z,x_p) = \exp\left[-\frac{4\pi}{3}v^3t_c^4\int_{x_i}^{x_p} dx I(x)\,(zr(x) + y(x_p,x))^3\right] \tag{3}$$

where

$$y(x,x\prime) = \int_{x\prime}^{x} r(x\prime)/r(x\prime\prime)dx\prime\prime \tag{4}$$

In order to find the minimum size and the size-distribution of the QNs we follow the procedure of Kodama *et al* [9]. The distribution function, in terms of z, is given by[8, 9]

$$F(z) = \frac{R^4(t_i)}{v^4 t_c^4} f(z) \tag{5}$$

where

$$\begin{aligned} f(z) &= \frac{3\,\theta(z-\alpha)}{4\pi\alpha^3}\left[-P'(X-\alpha) - \frac{3P(X-\alpha)}{\alpha}\right. \\ &+ \left.\frac{1}{\alpha^2}\int_0^\infty d\eta P(\eta+X-\alpha)\left\{\lambda e^{(-\lambda\eta/\alpha)} + \omega e^{(-\omega\eta/\alpha)} + \bar{\omega} e^{(-\omega\eta/\alpha)}\right\}\right] \end{aligned} \tag{6}$$

The solution of the equation $F(\alpha) = 0$ gives the minimum size, α, of the quark-nugget. The number of nuggets per unit volume is then

$$n_Q = R^{-3}(t_p)\int_\alpha^\infty F(X)dX = R^{-3}(t_p)\int_\alpha^\infty \frac{R^3(t_i)}{v^3 t_c^3} f(z)dz \tag{7}$$

The volume of each quark nugget is given by $\frac{4}{3}\pi(zvt_c)^3$. Since visible baryonic matter constitutes only ten per cent of the closure density ($\Omega_B = 0.1$ from standard big bang nucleosynthesis), a total of 10^{50} baryons will close the universe baryonically at $T = 100$ MeV. We emphasize at this point that these QNs would not disturb the standard primordial nucleosynthesis results. Therefore, if we assume that the total baryon content of the dark matter is carried by the quark nuggets then,

$$N_B = 10^{50}(100/T(MeV))^3 = V_H \frac{4\pi R^3(t_i)}{3R^3(t_p)}\rho\int_\alpha^\infty f(z)z^3 dz \tag{8}$$

where V_H is the horizon volume and ρ is the baryon density inside each nugget. We have taken $\rho = 0.15 fm^{-3}$ and $v = 0.5$ in the present calculation. The above equations are then solved self-consistently to obtain α and t_p. These values are then used to study the size-distribution of the quark nuggets. To calculate the size distribution of QNs we have used the nucleation rates proposed by Csernai and Kapusta [10].

Once the baryon density inside the nuggets is known one can easily translate from z to n_B (baryon number of a particular QN). In fig. 1 we have plotted the distribution of QN, $f(n_B)$, as a function of n_B. We see that for $T_c = 100MeV$ there is no quark nugget below $n_B = 10^{46}$ and above $n_B = 10^{47.5}$. For $T_c = 150MeV$ there is no quark nugget below $n_B = 10^{41.5}$ and above $n_B = 10^{43.5}$. Earlier studies [7] have shown that the nuggets having baryon number less than 10^{42} will not survive till the present epoch. So all the nuggets for $T_c = 100MeV$ will survive and some of the nuggets for $T_c = 150MeV$ will survive.

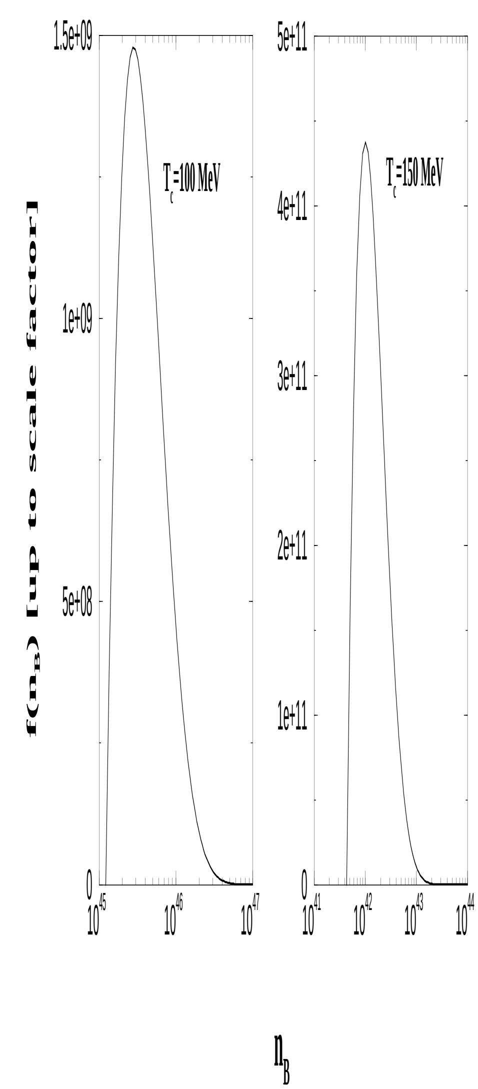

Figure 1: Distribution of QN, $f(n_B)$, as a function of n_B using nucleation rate proposed by Csernai and Kapusta. The value of surface tension is $50MeV fm^{-2}$.

3 Conclusion

In this work we have estimated the abundance of quark nuggets in various nucleation scenarios with different values of critical temperature. We have found that within a reasonable set of parameters QNs may be a possible candidate for cosmological dark matter.

One of us (JA) is grateful to Japan Society for Promotion of Science (JSPS) for financial support.

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