Diffusion coefficients and constraints on hadronic inhomogeneities in the early universe.

Sovan Sau, Sayantan Bhattacharya, and Soma Sanyal

University of Hyderabad Prof.C.R.Rao Road, Hyderabad, India 500046

Abstract

Hadronic inhomogeneities are formed after the quark hadron phase transition. The nature of the phase transition dictates the nature of the inhomogeneities formed. Recently some scenarios of inhomogeneities have been discussed where the strange quarks are in excess over the up and down quarks. The hadronization of these quarks will give rise to a large density of hyperons in addition to the protons and neutrons which are formed after the phase transition. These unstable hyperons decay into pions, muons and their respective neutrinos. Hence the plasma during this period consists of neutrons, protons, electrons, muons and neutrinos. Due to the decay of the hyperons, the muon component of the plasma will be very high. We study the diffusion of neutrons and protons in the presence of a large number of muons immediately after the quark hadron phase transition. We find that the presence of the muons enhances the diffusion coefficient of the neutrons/protons between 100 - 1 MeV. As the diffusion coefficient is enhanced, the inhomogeneities will decay faster in the regions where the muon density is high. Hence smaller inhomogeneities will be wiped out in muon rich regions. The decay of the hyperons will also generate muon neutrinos. Since the big bang nucleosynthesis provides constraints on the neutrino degeneracies, we revisit the effect of non zero degeneracies on the primordial elements.
I. INTRODUCTION

The quark hadron phase transition in the early universe resulted in the formation of hadrons at around 200 MeV. Before the phase transition, the baryon number was carried by the nearly massless quarks, while after the phase transition the baryon number is carried by the heavier hadrons. It has been proposed that if the phase transition is a first order phase transition, baryon number gets concentrated in between the bubble walls and baryonic inhomogeneities are formed at the end of the phase transition [1]. These baryon inhomogeneities affect the standard nucleosynthesis calculations. Later, lattice studies seemed to indicate that the phase transition is either a second order or a cross-over. However, even if the phase transition is not a first order transition, there is still the possibility of trapping a higher density of quarks in different regions and generating baryon inhomogeneities. There are scenarios where collapsing $Z(3)$ domain walls generate inhomogeneities[2, 3]. Dense inhomogeneities result in metastable quark nuggets [4]. Metastable H dibaryons have also been predicted due to the presence of s-quarks at the time of the quark hadron transition [5]. All these scenarios lead to an inhomogeneous distribution of baryon number across the universe after the quark hadron transition.

As the temperature cools down, neutrons and protons from these overdense region gradually diffuse to the underdense regions. The diffusion of neutrons and protons through the overdensities has been discussed previously in ref.[6–8]. When the diffusion of the neutrons and protons are studied, the standard interactions considered are the interactions between the neutrons, protons and electrons. The reason being that the other hadrons formed would decay in a short span of time. Even though the muon is an important part of the plasma at that temperature, none of these calculations considered the collision of the neutrons (or protons) with the muons. In this article, we argue that there are certain scenarios, where the muon density in the plasma cannot be neglected. If we look at the overdensities formed by the collapsing $Z(3)$ domains, we notice that a larger number of strange quarks are trapped as compared to the up and down quarks [9]. This means there would be a large production of hyperons immediately after the phase transition. The hyperons would decay almost immediately but would result in the formation of a large number of pions and muons. Pions would also subsequently decay into muons. Detailed discussion on the evaporation of quark nuggets formed in various cosmological scenarios also indicate that they mostly decay by the
emission of kaons. Kaons themselves have a short lifetime and would subsequently decay into muons. There have also been discussions of antimatter domains formed after the quark hadron transition which produce a large number of pions. These pions will also decay into muons. We therefore feel that there is every possibility that the baryon overdensities formed immediately after the quark hadron transition would have a significant number of muons too. Thus the diffusion coefficient of the protons and neutrons should also include their interaction with the muons. We would like to emphasize that this will be applicable mostly to the diffusion coefficients immediately after the quark hadron phase transition. A recent study [10] has shown that during this time (which is often referred to as the beginning of the lepton era), the inclusion of muons will increase the bulk viscosity roughly by a 100 million times. Therefore we feel that it is important to study the decay of hadronic inhomogeneities with the presence of the muons in the plasma.

In this work we find the diffusion coefficient of the nucleons in the presence of muons. Generally at temperatures above 1 MeV, neutrons and protons are in equilibrium with respect to weak interactions. Most of the studies of diffusive segregation of neutrons and protons are at temperatures below 1 MeV. At this temperature, the weak interactions fall out of equilibrium and the neutron being neutral moves faster than the proton. We break up our study in two parts, in the first one we look at temperatures from 100 MeV to 1 MeV. Here the neutrons and protons change continuously into one another through weak interactions so the particles are treated as indistinguishable. Below 1 MeV, we make a distinction between the neutrons and the protons. The number density of muons will be higher immediately after the phase transition. We find the nucleon - muon scattering cross section in the temperature range of 100 MeV - 1 MeV. This gives us the diffusion coefficient of the nucleons in these temperature ranges. We then use the diffusion coefficient to study the decay of inhomogeneities in the era after the quark hadron phase transition.

The other fall out of the decay of the unstable particles is the production of a large amount of muon neutrinos. This changes the muon neutrino chemical potential. Neutrino degeneracy and its effect on nucleosynthesis has been studied before [11]. Constraints on antimatter domains and other baryon inhomogeneities have also been obtained from nucleosynthesis calculations [12]. We revisit some of these calculations for the case of inhomogeneities which have a pre-dominance of strange quarks. As mentioned before, such inhomogeneities would form from the collapse of Z(3) domains around the time of the quark hadron transition.
Though, it is difficult to draw stringent constraints from the nucleosynthesis results due to the fact that it is a combination of all three neutrino degeneracies, one can still put some bounds on the muon neutrino degeneracy. We use one of the available nucleosynthesis codes based on the Wagoner - Kawano code and modified by S. Dodelson \cite{14} to look for constraints coming from nucleosynthesis. The nucleosynthesis code allows us to change the neutrino degeneracy parameters and obtain the abundances of the primordial elements. There have been previous studies of the effect of neutrino degeneracies on nucleosynthesis \cite{11}. These are over a very wide range of baryon to photon ratios. We confine ourselves to the current value of the baryon to photon ratio and obtain the primordial abundances for different values of the chemical potentials for muon neutrino ($\xi_\mu$) and the electron neutrinos ($\xi_e$).

In the next section, we briefly discuss the diffusion of the nucleons through a plasma consisting of neutrons, protons, electrons and muons. In section III, we follow it up by calculating the diffusion coefficients numerically and using the diffusion equation to show the effect of the presence of the muons in the plasma. In section IV, we discuss the decay of the inhomogeneities in a muon rich plasma and compare it to the decay in an electron rich plasma. In section V, we discuss the effect of muon neutrinos and obtain constraints on the inhomogeneities based on the muon neutrino degeneracy parameters. Finally in section VI, we present our conclusions and some brief discussions.

II. DIFFUSION COEFFICIENTS OF NUCLEONS

The diffusion coefficient of nucleons have been studied in detail in both refs.\cite{6} and \cite{7}. Both these and other references study the coefficients after the weak interactions have fallen out of equilibrium i.e for temperatures less than 1 MeV. However, overdensities are formed at around $200 - 100$ MeV. So diffusion of the nucleons from the overdense regions start around the same time. Since the weak interactions are in equilibrium, the protons and neutrons are indistinguishable at these temperatures. But the hadrons would still try to move from an overdense region and restore equilibrium in the baryon number distribution. The neutrons and protons would collide with the electrons and would decay into each other. Other hadrons like the hyperons will decay and produce pions and muons. Finally, the plasma will consist of protons, neutrons, electrons, muons and their respective neutrinos.
We would like to find out the diffusion coefficient of the nucleons at these temperatures. We will therefore concentrate on the nucleon-electron and the nucleon-muon cross sections.

In a gas of lighter particles, the diffusion coefficient of a heavier particle is defined by the Einstein’s equation \( D = b T \). Here, \( b \) is the mobility of the heavier particle and \( T \) is its temperature. For a Maxwellian distribution of particles, it is given by

\[
b^{-1} = \frac{16\pi}{T} \int \frac{p^2 dp}{3h} \sigma_i e^{-E/T}
\]

Here \( \sigma_i \) is the scattering cross-section, and \( v \) is the velocity of the particles.

Since there are different kinds of particles in the plasma, we are dealing with multi-particle diffusion here. This depends on the concentration of the particles of different species in the plasma. The effective or average diffusion coefficient that is used for multi-particle diffusion is given by [15],

\[
\frac{(1 - x_i)}{D_i} = \sum_{i \neq j} x_j \frac{D_{ij}}{D_{ij}}
\]

Here \( i \) and \( j \) denote different particles of the plasma. Since we do not consider collision of similar particles here we have taken \( i \neq j \). If \( N \) be the total particle density, and \( n_i \) be the number density of the \( i^{th} \) particle, then \( x_i = \frac{n_i}{N} \).

We now proceed to obtain the scattering cross-sections which are required to obtain the diffusion coefficients in our case. The nucleon-electron cross section is dominated by form factors. The neutron-electron and the proton-electron scattering cross-sections are not the same due to the presence of the electric or Mott scattering cross-section in the latter. So let us consider a region in the universe, where the neutrons are more in number. The diffusion coefficient due to the neutron-electron cross-section can be obtained by considering \( F_1(q^2) = 0 \) and \( F_2(q^2) = 1 \). Here \( F_1(q^2) \) and \( F_2(q^2) \) are the Dirac and Pauli form factors. We do not derive the cross-section explicitly here as the derivation has been discussed in detail, previously in the literature [6].

As mentioned before we are looking at the mobility of a heavy particle passing through a gas of light particles. Here, the neutron is the heavier particle and we assume that it is moving through a electron-positron gas. Substituting the expression for the cross-section in the definition of the diffusion coefficient, we obtain,

\[
D_{ne} = \frac{M^2}{32m^3 \alpha \kappa^2} \frac{1}{T f(T)} \text{e}^{1/T}.
\]
\( M \), here is the neutron mass, \( m \) is the electron mass, \( \kappa = -1.91 \) is the anomalous magnetic moment and the temperature is dimensionless as it is scaled by a factor of \( m_e c^2 \). We also have \( f(T) = 1 + 3T + 3T^2 \).

Similar to the nucleon-electron cross-section, we also obtain the nucleon-muon scattering cross-section. The amplitude of the muon vertex is similar to the electron vertex. It is given by \(-ie\gamma^\nu (q^2)\). Though the muon is heavier than the electron, it is still lighter than the neutron. Hence we can still consider its mass to be much smaller than the neutron mass. The heavier neutron will not move very fast compared to the lighter particles, therefore we can consider \( q^2 \approx 0 \). The form factors will then be \( F_1 = 0 \) and \( F_2 = 1 \). The neutron vertex is given by \( \Gamma_\mu (q^2) = \frac{i\kappa}{2M} \sigma_{\mu\nu} q^\nu \). The differential cross-section will then be,

\[
\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \kappa^2 q^2}{8M^2 E^2 \sin^4(\theta/2)} \frac{1}{1 + 2E \sin^2(\theta/2)/M} \left[ \cos^2(\theta/2) \left( \frac{q^2}{4M^2} - 1 \right) - 2 \sin^2(\theta/2) \right] \] (4)

We assume that the muon energy and mass are less than the neutron mass. This simplifies the cross-section and we can get an approximate cross-section given by,

\[
\frac{d\sigma}{d\Omega} \approx K \frac{\alpha^2 \kappa^2}{4M^2} \left[ 1 + \cosec^2(\theta/2) \right] \] (5)

Here the constant \( K = \frac{1}{2} \). We have also assumed that the heavy neutron particle is moving through a muon-antimuon gas. The mobility of the neutron is given by the force on the neutron due to the medium. This force is given by the interaction cross section. Substituting in the definition of the diffusion constant, the diffusion coefficient of the neutron through the muon-antimuon gas is given by,

\[
D_{n\mu} = \frac{M^2}{32m_\mu^3 \alpha \kappa^2 T f(T')} \] (6)

Here \( T' = \frac{T}{m_\mu c^2} \). Now that we have both \( D_{ne} \) and \( D_{n\mu} \), we can get the total diffusion coefficient for the neutron moving through the plasma of electrons, muons and their anti-particles. From equation (1), we see that it depends on the concentration of the particles in the plasma. We do not know the exact concentration of electrons and muons after the quark hadron transition. Therefore we study how the diffusion coefficient changes depending on the change in the concentration of the electrons and the muons. In the next section, we present the results.
III. DIFFUSION COEFFICIENTS AT THE BEGINNING OF THE LEPTON ERA

We initially look at the diffusion coefficient close to 100 MeV. The quark hadron phase transition occurs around 200 MeV. The inhomogeneities are formed after the phase transition. As mentioned in the introduction, inhomogeneities with a large number of strange quarks will hadronize to give a large number of hyperons immediately after the phase transition. These hyperons have a short lifetime and decay into pions and muons. The pions too subsequently decay into muons. So the number density of muons would be high around these temperatures. Since the plasma has the nucleons, electrons and the muons, we are using the multiparticle diffusion coefficient mentioned previously. Also it is difficult to handle too many unknown variables, so initially we keep the number density of neutrons fixed and vary the number density of the muons and the electrons. We also assume that the neutron density is less than the combined electron and muon densities. As $x_i$ is the fractional number density, we have the constraint that $\sum_i x_i = 1$. For the first case, since $x_n$ is kept constant, there will be three possibilities, (1) $x_e < x_\mu$ (2) $x_e \approx x_\mu$ and (3) $x_e > x_\mu$.

Based on these, we plot the total $D_n$ vs temperature in fig 1. The three lines which denotes each of the three cases are as follows, the (red) solid line denotes case (1), the (green) dashed line denotes case (2) while the (blue) dotted line denotes case (3). Now, if the particle densities depend solely on temperature (i.e in the absence of any inhomogeneities) then between 10 MeV and 100 MeV the electron particle density will always be greater than the muon particle density [10]. This is the case (3) in fig 1. As the temperature decreases, the diffusion coefficients increase. The presence of the inhomogeneities however increases the number density of the muons. As the number density of muons increase, we notice that the diffusion coefficient is increasing. Thus the presence of muons changes the diffusion coefficient of the neutron considerably. This will definitely affect the decay of hadronic inhomogeneities between 100 MeV to 1 MeV.

Here, we had considered the neutron number density to be constant but that may not be the case. So we have to look at the other possibilities too. We consider a second possibility, where it is the electron density that is kept constant and is less than the combined density of the other particles. We now vary the neutron density and the muon density and see the effect on the diffusion coefficient. This time the constraint is that $x_e$ is kept a constant and we have three cases again. They are (1) $x_n < x_\mu$ (2) $x_n \approx x_\mu$ and (3) $x_n > x_\mu$. We plot...
Figure 1: Diffusion coefficient of neutrons in the electron, neutron and muon plasma. The (red) solid line denotes $x_e < x_\mu$, the (green) dashed line denotes $x_e \approx x_\mu$ while the (blue) dotted line denotes $x_e > x_\mu$.

Figure 2: Diffusion coefficient of neutrons in the electron, neutron and muon plasma. The (blue) dotted line denotes $x_n > x_\mu$, the (green) dashed line denotes $x_n \approx x_\mu$ and the (red) solid line denotes $x_n < x_\mu$.

the diffusion coefficients in fig 2. As before the (red) solid line denotes case (1), the (green) dashed line denotes case (2) while the (blue) dotted line denotes case (3). As the figures show, keeping the electron density constant and varying the neutron density does not change the nature of the graphs. We still see that the diffusion coefficient starts to increase as the
muon density is increased. Thus these graphs show that the presence of the muons changes the diffusion coefficient of the neutron through the plasma. The diffusion coefficient being increased, the neutrons move faster through the plasma. So a region which has a higher neutron density will diffuse at a faster rate at these temperatures.

We also calculate the diffusion length as a function of temperature. In fig. 3 we plot the temperature vs diffusion length. We find that the diffusion length increases as temperature decreases. In the case when the muon density is higher in the plasma, the rate of increase of the diffusion length increases considerably after 10 MeV.

However, this only happens towards the beginning of the lepton era. As the temperature cools to 1 MeV, the number density of muons go down. During this period, the contribution to the diffusion coefficient from the muons becomes negligible. Fig. 4 gives the diffusion coefficient at temperatures less than 1 MeV. As seen from fig. 4, the presence of the muons does not really change the diffusion coefficient much below 1 MeV. We have thus established that the diffusion coefficient of the neutrons changes significantly due to the presence of the muons in the plasma at the beginning of the lepton era. We would now like to see what effect these new diffusion coefficients would have on the diffusion of hadronic inhomogeneities formed around the time of the quark hadron phase transition.

Figure 3: Diffusion length of neutrons in the electron, neutron, muon and neutrino plasma. The (violet) dashed line denotes $x_\mu > x_e$, and the (red) dot-dashed line denotes $x_\mu < x_e$. 

We now look at the decay of inhomogeneities in the presence of the muons. Baryon inhomogeneities generated at the quark hadron phase transition should be at least of the scale of 0.4 m (at 200 MeV) to affect nucleosynthesis calculations. So the overdensities that may affect the nucleosynthesis results will be greater than 0.5 m. This scale is still quite small compared to the size of the universe at that time which is of the order of a few kilometers. Since the size of the inhomogeneity is very small compared to the size of the universe at that temperature, we can ignore the effect of the expanding universe on the decaying inhomogeneities.

Initially, we look at the diffusion of the inhomogeneities at a fixed time $t$. We fix the temperature at 100 MeV. As mentioned before we have neglected the Hubble constant. We treat the inhomogeneity as a thin film. The boundary conditions of the film being, at $x = 0$, the number density is very high and at large values of $x$, it goes down to zero. This boundary condition is chosen as the size of the inhomogeneity is much smaller than the size of the horizon at that temperature. In general, the diffusion equation is given by,

$$\frac{D(t)}{a^2} \frac{\partial^2 n(x, t)}{\partial x^2} = \frac{\partial n(x, t)}{\partial t} = -\lambda^2$$
Figure 5: Solution of the diffusion equation at 100 MeV. The (blue) dotted line denotes \(x_e > x_\mu\), the (green) dashed line denotes \(x_e \approx x_\mu\) while the (red) solid line denotes \(x_e < x_\mu\).

where \(\frac{D}{\alpha^2}\) is just a constant coefficient. The initial number density is taken to be of the order of \(10^{20}\) and it is assumed to form after the quark hadron phase transition. A static solution of the equation at \(T = 100\) MeV is given in fig 5. The three lines correspond to the three cases in fig. 1. Here again we have the neutron ratio to be constant and vary the amount of electrons and muons.

We see that the inhomogeneities have gone down significantly in the muon rich plasma. Though they have the same initial overdensity, the overdensity at \(T = 100\) MeV is \(4.5 \times 10^{10}\) for an electron rich plasma while it is \(1.5 \times 10^{10}\) in a muon rich plasma. Similarly, we can obtain the solution at 100 MeV for the case of the electrons being in a fixed ratio and varying the neutron and the muon ratios. This would correspond to diffusion coefficients from the second figure.

As expected, we see that the level of the inhomogeneities have decreased considerably in a muon rich plasma while they are much higher in an electron or neutron rich plasma. However, these are static solutions which do not take into account the time dependent part of the diffusion coefficient. So we also solve the time dependent diffusion equation numerically to see the evaluation of the inhomogeneities with time. The diffusion coefficient is time dependent. We use a finite difference method to obtain the numerical solution of the diffusion equation for the different diffusion coefficients defined previously.

Our diffusion coefficient is expressed in terms of temperature. Hence we use the stan-
Figure 6: Solution of the diffusion equation at 100 MeV. The (blue) dotted line denotes $x_n > x_\mu$, the (green) dashed line denotes $x_n \approx x_\mu$ and the (red) solid line denotes $x_n < x_\mu$. 

By using the standard time temperature expression to obtain the diffusion equation in terms of temperature. Therefore, now our number density depends on space and temperature $n(x, T)$. We consider the inhomogeneity at $T = 100$ MeV, we then evolve the inhomogeneity with a given diffusion coefficient. We assume for the time being that the ratio of the muons to the nucleons are more or less constant through out the time of evolution of the diffusion equation. That way the diffusion coefficient is only dependent on temperature. Initially the number density decreases slowly. As time increases (temperature decreases), the peak of the inhomogeneity goes down and it spreads out in space. However, it is only after 10 MeV, that the difference in the number density becomes significant. So we have plotted the number densities at temperatures lower than 10 MeV. In Fig. 7, we present the decay of the inhomogeneity, in an electron rich plasma while in fig. 8 we have plotted the decay in a muon rich plasma. From the two plots, it is clear that the inhomogeneities decay faster in a muon rich plasma. The difference in the decay increases as the temperature cools to 1 MeV. We have shown the end stages in fig. 7 and 8. The final profile of the inhomogeneity for the muon case is closer to $2 \times 10^{14}$ while in the electron rich case it is above $5 \times 10^{14}$. The initial size of the inhomogenity was the same in both cases, so it indicates that the hadronic inhomogeneity decays nearly twice as fast in the presence of a large muon density. This leads us to conclude that over densities which have a larger number of strange quarks will decay away faster after hadronization. Thus they will have little or no impact on the Big Bang Nucleosynthesis
Now inhomogeneities formed due to the collapse of the $Z(3)$ domain walls as mentioned before will have a larger number of strange quarks. These quarks when they hadronize will form unstable hyperons. The hyperons decay into mesons and neutrinos. Since most of them will decay due to the production of pions and pions further decay into muon and

V. NEUTRINO DEGENERACY PARAMETERS

Now inhomogeneities formed due to the collapse of the $Z(3)$ domain walls as mentioned before will have a larger number of strange quarks. These quarks when they hadronize will form unstable hyperons. The hyperons decay into mesons and neutrinos. Since most of them will decay due to the production of pions and pions further decay into muon and
muon neutrino, there will be a larger number of muon neutrino in the plasma.

Generally, it is assumed that the three standard model neutrinos oscillate amongst themselves and have the same chemical potential at a given temperature. So in the nucleosynthesis calculations the three neutrinos are usually given the same chemical degeneracy parameter. However, it has also been shown previously, that if the lepton number densities are different for the electron neutrino and the muon and tau neutrino, then the abundances of primordial elements are affected [11]. Therefore if $Z(3)$ domain walls collapse and form inhomogeneities during the quark hadron phase transition, we can expect a larger number density of muon neutrinos compared to electron neutrinos. If $L_{\nu e}$ and $L_{\nu\mu}$ be the number densities of the electron and muon neutrinos respectively, we will have $L_{\nu\mu} > L_{\nu e}$. The lepton numbers are given by [17],

$$L_{\nu i} \approx \frac{\pi^2}{12\zeta(3)} \left(\frac{T_\nu}{T_\gamma}\right)^3 (\xi_i + \frac{\xi_i^3}{2\pi^2}). \quad (8)$$

Here $\xi_i = \frac{\mu_{\nu i}}{T_\nu}$ is the neutrino degeneracy parameter which determines the energy density of the neutrinos during nucleosynthesis.

Now for $Z(3)$ domain walls, one can see that the number density of strange quarks is about 10 times that of the up and down quarks [3]. So there is a possibility that $L_{\nu\mu}$ can be about 10 times larger than $L_{\nu e}$. However, we are assuming that all the up and down quarks form neutrons and protons while the strange quarks hadronize to hyperons. This assumption may not be completely correct. Since the decay of the hyperons produces the excess muon neutrinos, the final values may however be far less. So we treat this as an upper bound only. The lower bound would be the case that the neutrino degeneracy parameters are considered as zero. Based on these bounds, we look at the abundances of the light elements to see if we can obtain some constraints on the baryonic inhomogeneities.

We have used a standard code for the nucleosynthesis calculations. The core of the computational routines is based on Wagoner’s code [13] but the code itself has been modified by Scott Dodelson [14]. The code allows us to change the neutrino degeneracies at the beginning of the calculation. The current bound on the baryon to photon ratio is quite stringent. Hence we just adhere to only one value of the baryon to photon ratio. Neutrino degeneracies have been studied previously and some bounds on the degeneracy values have already been obtained [11]. The neutrino degeneracy affects the helium and the lithium abundances more than the other abundances so we just look at the primordial helium and
lithium abundances. In fig. 9, we show the abundances for $\xi_e = \xi_\mu$ in bold while we have $\xi_e < \xi_\mu$ as the dashed line. We have considered $\eta = 3.4 \times 10^{-10}$. There are two pairs of values we have considered. One of them is $\xi_e = 0.2$ and $\xi_\mu = 2.0$, while the other is $\xi_e = 0.4$ and $\xi_\mu = 4.0$.

Our results show that there are some small changes in the abundances of helium. The changes are not too significant to put constraints on the inhomogeneities. However, the lithium abundance is enhanced if we go to higher values of the degeneracies. Here, we have kept the muon neutrino degeneracy to be higher than the electron neutrino degeneracy at all times. Since the inhomogeneities in our model tend to decay into pions and muons, the muon neutrino degeneracy will definitely be higher than the electron neutrino degeneracy. This means that the lithium abundance will be higher than the current calculated value. As is well known, the observed lithium abundance is less than the calculated value, hence we can conclude that large inhomogeneities with a predominance of strange quarks will be constrained by the lithium abundance.

Apart from the inhomogeneities from the collapsing $Z(3)$ domains, there can be charged inhomogeneities too. Charged inhomogeneities can be formed if the plasma has a small charge imbalance during the quark hadron transition [18]. So we also look at the case where the electron neutrino degeneracy is greater than the muon neutrino degeneracy. This can happen if there are charged inhomogeneities in the plasma. The plot is given in fig. 10. Here however we see that both the helium abundance and the lithium abundance is reduced. Not only that, the large electron neutrino density also affects the neutron to proton

Figure 9: Comparison of abundances in the presence and absence of inhomogeneities for muon degeneracy greater than the electron degeneracy.
transformation rates. Thus the beginning of the lithium production is also delayed.

Here, we notice that when the two parameters $\xi_\mu$ and $\xi_e$ are varied there is variation in the abundances of lithium and helium. When $\xi_\mu > \xi_e$, the two abundances are enhanced while if $\xi_\mu < \xi_e$ the abundances are decreased. Since the decay of the inhomogeneities results in the variation of the degeneracy parameters, a detailed simulation would give us further insight in understanding the quark hadron phase transition.

VI. SUMMARY AND CONCLUSIONS

In summary, we have shown that baryonic inhomogeneities decay faster in a muon rich plasma compared to an electron rich plasma. Generally, in the absence of inhomogeneities the plasma has a higher electron density compared to the muon density. In the presence of inhomogeneities however, the number density of muons is increased. It is quite possible that the muon density would be higher than the electron density in the plasma. Such a scenario has never been studied before. We obtained the diffusion coefficient of the neutron in a muon rich plasma and find that between 100 MeV to 1 MeV it increases significantly. This significant increase will result in the faster decay of inhomogeneities around 1 MeV. For an electron rich plasma, the size of the inhomogeneities need to be of the order of 0.4 m for them to survive till the nucleosynthesis epoch. But in a muon rich plasma, the size of the inhomogeneity has to be at least twice that size to survive to the nucleosynthesis epoch. So any mechanism that segregates the strange quarks more than the up and down
quark must generate very large inhomogeneities to have any effect on the nucleosynthesis calculations. Inhomogeneities which have a predominance of strange quarks thus decay faster than inhomogeneities which have the different quarks in a more or less equal proportions.

We have also looked at neutrino degeneracies generated by these inhomogeneities. Inhomogeneities which have a predominance of strange quarks will also generate a larger number of muon neutrinos compared to electron neutrinos. This means it is quite possible that a large muon neutrino degeneracy parameter is generated. We have checked whether a large muon degeneracy parameter is compatible with nucleosynthesis calculations. We find that the lithium abundance is higher than the observed lithium abundance. This puts some constraints on these inhomogeneities. Further constraints can also be obtained if a more detailed simulation of the decay of the inhomogeneity is carried out. We hope to pursue this in a later work.

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