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STERILE NEUTRINOS IN THE EARLY UNIVERSE

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ABSTRACT. We discuss the role played by right-handed sterile neutrinos in the early universe. We show how the well known ^4He constraint on the number of relativistic degrees of freedom at early times limits the equilibration of the right-handed neutrino sea with the background plasma. We discuss how this allows interesting constraints to be placed on neutrino properties. In particular, a new limit on the Dirac mass of the neutrino is presented.

1. Introduction

If the presence of right-handed (RH) "sterile" neutrinos, ν_i^R , ($SU(2)_L \otimes U(1)_Y$ singlets) are allowed, then interesting scenarios can arise when mechanisms for their conversion into left-handed (LH) "active" neutrinos, ν_i^L , are introduced. Hereafter when we refer to RH neutrinos we mean both RH neutrinos and LH anti-neutrinos. By "sterile" here we mean that they do not transform under the standard model gauge group.

In the Standard Big Bang (SBB) model RH neutrinos play no role. Even if they exist they are assumed to have decoupled at $T > 100$ GeV. The neglect of RH neutrinos in nucleosynthesis calculations is to a large extent justified from consideration of the statistical weight, g , of the relativistic particles present before and after the QCD phase transition. Since the evolution of the universe through phase-transition and particle-annihilation epochs is characterized by constant *co-moving* entropy density, the amount of heating of the LH sea relative to the RH sea is given by $T_{LH}/T_{RH} = (g_1/g_2)^{1/3}$, where the subscripts 1 and 2 refer to the times before and after the annihilation epoch, respectively, and g_1 and g_2 are the effective statistical weights of relativistic particles at these times. Prior to confinement the statistical weight in relativistic particles is $g_1 \approx 56.5$; whereas, after the quarks are confined the only nearly relativistic strongly interacting particles will

be pions, so that $g_2 \approx 17.25$ and $T_{LH}/T_{RH} \approx 1.5$. This implies that at the time of nucleosynthesis the relative energy densities in a LH and RH neutrino species will be $\rho_{LH}/\rho_{RH} \approx 5$, so that a sterile neutrino species counts as less than 1/5 of an additional neutrino flavor. Muons and pions should annihilate or drop out of equilibrium at roughly $T \approx 100$ MeV, and if we add their statistical weight to the differential heating of the LH and RH seas then a RH neutrino species would count for only about 0.1 of an additional flavor.

SBB nucleosynthesis predicts that the number of relativistic neutrino species be constrained by [1]

$$N_\nu \leq 3.4 + 20 \left(\frac{Y_p - 0.240}{0.240} \right), \quad (1)$$

where Y_p is the primordial ${}^4\text{He}$ mass fraction. If we take $Y_p = 0.23 \pm 0.01$ from observation [1-2] then $N_\nu \leq 3.4$. We stress here that our result will be sensitive to the adopted upper limit of $Y_p < 24\%$. A value of Y_p larger by even 0.2% would weaken our constraint. If we assume three light Dirac neutrinos and that the RH components of one of them did not decouple until after the QCD epoch, then those RH components would count for an extra 0.7 neutrino flavor. If the decoupling of the RH sea is after muon and pion annihilation then the RH components count for almost a full extra neutrino flavor. Even an extra 0.7 neutrino flavor is incompatible with the limit $N_\nu \leq 3.4$, thus the RH components of the neutrino (ν_μ or ν_τ) would have to decouple prior to the QCD epoch, which we define to occur at a temperature $T = T_{QCD}$.

It is important to note here that because this argument is based on added degrees of freedom contributed by the RH neutrinos we must assume that neutrinos are purely Dirac particles. Any Majorana contribution to the neutrino mass term will invalidate the argument.

A particle species, x , is decoupled from the background plasma when

$$\sum_i n_i \sigma \ll H, \quad (2)$$

where σ is the cross section of the interaction processes involving x , and H is the Hubble parameter which can be written as

$$H = \left(\frac{4\pi^3}{45} \right)^{1/2} m_{pl}^{-1} g^{1/2} T^2, \quad (3)$$

where m_{pl} is the Planck mass.

Several studies have used the necessity that any RH neutrino species be decoupled prior to the QCD phase transition to impose constraints on the mass, electromagnetic, oscillation and weak interaction properties of neutrinos.

2. Neutrino Mass

Consider a neutrino of mass m_ν and energy E_ν . One can show that the cross section for helicity-flip in any scattering event is given by [3-4]

$$\sigma_R \sim \sigma_L \left(\frac{m_\nu}{E_\nu} \right)^2, \quad (4)$$

where $\sigma_L \sim G_F^2 T^2$ is the cross section for the normal non-flip scattering event (G_F is the Fermi coupling constant). Demanding that eq. (3) be valid at $T = T_{QCD}$ and adopting statistical weights relevant to the epoch prior to quark confinement, leads to the following constraint on the neutrino mass [5]

$$m_\nu \ll 150 \text{ keV} \left(\frac{100 \text{ MeV}}{T_{QCD}} \right)^{1/2}. \quad (5)$$

Assuming $T_{QCD} \sim 100 \text{ MeV}$, we find a cosmological limit of $m_\nu \ll 150 \text{ keV}$. The present experimental upper limits for the muon and tau neutrino are 250 keV and 35 MeV, respectively [6].

Finally, we note that if the tau neutrino is too massive ($m_\nu \gtrsim 1 \text{ MeV}$) then it can become non-relativistic during nucleosynthesis [7]. In such circumstances the universe is matter dominated as it passes through nucleosynthesis and the nucleosynthesis yields can be perturbed from their SBB values. This effect should modify somewhat the limit of eq. (5).

3. Other Constraints

The RH neutrino sea can be populated through other effects such as electromagnetic interactions, oscillations, or new forms of weak interactions. For example, similar arguments to those given above have been previously adopted in order to constrain the neutrino magnetic moment, μ_ν , viz., $\mu_\nu < 2 \times 10^{-11} \mu_B$ [8], where μ_B is the Bohr magneton. Similarly, the neutrino charge radius, r , is constrained by $\langle r^2 \rangle \lesssim 10^{-32} \text{ cm}^2$ [9]. The ^4He observation coupled with simple extensions of the standard electroweak model, leads to the following constraint on G_R , the RH-coupling constant,

$$G_R \lesssim G_F T_{QCD}^{-3/2}. \quad (6)$$

For $T_{QCD} \sim 100$ MeV results in $G_R \lesssim 10^{-3} G_F$ [10-11]. In addition, if $G_R \propto M_{W_R}^{-2}$, where M_{W_R} is the mass of W_R (the RH counterpart of the LH intermediate vector boson W_L), then this leads to the constraint

$$M_{W_R} \gtrsim M_{W_L} \left(\frac{T_{QCD}}{1 \text{ MeV}} \right)^{3/4}, \quad (7)$$

which for $T_{QCD} \sim 100$ MeV results in $M_{W_R} \gtrsim 2.5$ TeV [11]. The importance of RH neutrinos in the context of neutrino oscillations has also been previously discussed [12].

4. Conclusions

We have discussed the constraints imposed on Dirac neutrinos derived from considerations of their spin flipping into sterile RH neutrino states. Such flipping is severely constrained by the inferred primordial ^4He abundance. We showed in particular, how this astronomical observation imposes a mass limit of order 150 keV on the Dirac neutrino.

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