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NEW INSIGHTS ON MAJORON MODELS

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Majoron models are extensions of the standard model in which the global $B - L$ symmetry is spontaneously broken. The associated Nambu-Goldstone boson is called the Majoron (J). There are various such models. Of these, recent measurements of the Z -width have ruled out the models in which the Majoron transforms like a triplet [1] or a doublet [2] of the weak $SU(2)_L$ group. Thus, only singlet Majoron models [3,4] are consistent with the Z -width, and we will restrict our discussion to the model of Chikashige, Mohapatra and Peccei (CMP) [3].

In this model, one introduces right handed neutrinos N_R and a gauge singlet Higgs S . The Yukawa couplings in the leptonic sector are given by

$$\bar{\psi}_L \lambda_D N_R \phi + \frac{1}{2} N_R^T C \lambda_M N_R S + \text{h.c.} \quad (1)$$

Here, ϕ is the Higgs doublet and ψ_L denotes the leptonic doublets, and λ_D, λ_M are matrices in the flavor space. In the vacuum, if $\langle \phi \rangle = v_2$ and $\langle S \rangle = v_1$, the global $B - L$ symmetry and the gauge symmetry are broken. The Majoron is given by $J = \text{Im } S$. The light neutrinos get a see-saw type mass matrix $m_\nu \sim \lambda_D \lambda_M^{-1} \lambda_D^T \cdot (v_2^2/v_1)$.

It has been recently pointed out that in this model, the ν_μ or the ν_τ can be

the dark matter of the universe [5]. It is well known that if neutrino scattering is larger than in the standard model, the problem of cosmological decoupling of neutrinos is very different from the standard expectation [6]. The number density n_ν comes out to be smaller than standard expectation, so that a larger range of masses are allowed. In this model, $\nu\nu \rightarrow JJ$ can provide such large scattering. Notice that such a channel does not imply that all neutrinos eventually annihilate into Majorons. When the density falls down below a critical value, it is hard for one neutrino to find another, so that the annihilation becomes ineffective in an expanding universe. The relic density of neutrinos is given by [5]

$$\Omega h^2 \simeq \left(\frac{v_1}{1 \text{ GeV}} \right)^4 \left(\frac{1 \text{ MeV}}{10 T_D} \right)^2 \quad (2)$$

where T_D , the decoupling temperature, is in the range $m_\nu/6$ to $m_\nu/16$ for $1 \text{ keV} < m_\nu < 35 \text{ MeV}$. For $m_{\nu_\tau} \sim 1-10 \text{ MeV}$, one can get $\Omega h^2 \sim 1$ if $v_1 \sim 1 \text{ GeV}$. Such a value of v_1 is neither unnatural nor untenable. Neutrinos behave like warm or cold dark matter in this scenario [6,5], which is acceptable for galaxy formation.

It has also been argued that the CMP model can explain baryogenesis in the universe [7]. The out-of-equilibrium con-

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dition is satisfied if the transition is first order. Baryon number is violated in the model through non-perturbative effects. The couplings of S can be complex, and therefore CP-violating. Thus, all conditions for baryogenesis are met in this model. To see how large the CP-violating effects can be, note that the Yukawa couplings are invariant under the redefinitions

$$\begin{aligned} \psi_L &\rightarrow V^\dagger \psi_L, & N_R &\rightarrow U^\dagger N_R, \\ \lambda_D &\rightarrow V^\dagger \lambda_D U, & \lambda_M &\rightarrow U^T \lambda_M U. \end{aligned} \quad (3)$$

A physical measure of CP violation should be invariant under the above transformation and should vanish when the coupling matrices are real. The simplest of such terms is [7]

$$\delta = \text{tr} \left(\lambda_D^\dagger \lambda_D \lambda_M^\dagger \left[\lambda_M \lambda_M^\dagger, \lambda_D^T \lambda_D^* \right] \lambda_M \right) \quad (4)$$

The baryon number to entropy ratio (η_B/s) generated will be given by δ/g_* , where g_* is the effective number of degrees of freedom, presumably $\mathcal{O}(10^2)$. For $\lambda_M \sim \mathcal{O}(1)$, Eq. (4) gives $\delta \sim \lambda_D^4 \leq m_{\nu_\tau}^2 G_F$. Thus, one obtains $\eta_B/s \sim 10^{-10}$ if $m_{\nu_\tau} \gtrsim 10$ MeV. Thus, ν_τ must be unstable in order to be cosmologically consistent.

The question of the stability of neutrinos in the CMP model has been of great interest. For the sake of convenience, we define a small parameter $\rho = \lambda_D \lambda_M^{-1} \cdot (v_2/v_1)$. Naively, one would expect [3] that the amplitude for the decay $\nu \rightarrow \nu' + J$ is of $\mathcal{O}(\rho^2)$. However, it was shown that at the tree level, the $\mathcal{O}(\rho^2)$ term is diagonal in the light neutrino fields [8]. The lowest order off diagonal terms [9] arise at $\mathcal{O}(\rho^4)$, and this gives a decay rate $\Gamma \sim (G_F^2/8\pi) m_\nu^5 \theta^2$,

where θ is an intergenerational mixing angle. This rate can be consistent with nucleosynthesis bounds as long as $\theta \gtrsim 10^{-3} (m_\nu/10 \text{ MeV})^{3/2}$.

Recent investigations [10], however, show that at one loop level, the decay amplitude is roughly given by $(1/8\pi^2) \rho^2 \theta$, which dominates over the tree amplitude for a wide range of neutrino mass and mixing. One gets

$$\begin{aligned} \Gamma &\sim \frac{m_\nu}{8\pi} \theta^2 (\rho^2/8\pi^2)^2 \\ &\sim 10^8 \text{ s}^{-1} \theta^2 (m_\nu/10 \text{ MeV})^3. \end{aligned} \quad (5)$$

For ν_τ , this means that the lifetime can be eight to ten orders of magnitude smaller than the tree level expectation. For ν_μ , the ratio can be even smaller. Thus, neutrinos are much more unstable in this model than previously thought. This fact will have interesting cosmological consequences, some of which are discussed in Ref. [10].

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