

MASS OF TAU NEUTRINO IN $SO(10)$ GUTS

G. BARENBOIM AND M. RAIDAL

*Departament de Física Teòrica, Universitat de València and
IFIC, Centre Mixte Universitat de València - CSIC
E-46100 Burjassot, Valencia, Spain*

Abstract

We investigate the allowed ranges of masses for an unstable tau neutrino in the context of $SO(10)$ GUT-s. In light of the new nucleosynthesis results we obtain that there is a narrow window for m_{ν_τ} where the LEP, neutrino oscillation and nucleosynthesis data are compatible. This window, which depends on the effective number of neutrinos contributing to nucleosynthesis, has important cosmological consequences and will be tested by ongoing neutrino oscillation and LEP II experiments.

December 1996

The question of understanding the smallness of the ordinary neutrino masses, m_{ν_e} , m_{ν_μ} and m_{ν_τ} , relies on different solutions in the context of extended gauge structures of the Standard Model (SM). The most attractive one, known as the see-saw mechanism [1], has been conceived in $SO(10)$ grand unified theories (GUT) [2]. In these theories, the light neutrinos are massive Majorana particles and, in general, mixed between flavour states. Neutrino mixing implies that the generational lepton numbers, like the electron number (L_e), muon number (L_μ) and tauon number (L_τ), are not conserved, giving rise to flavour changing processes like radiative decays of μ and τ leptons. Apart from these, another type of flavour changing decays of charged leptons, containing only charged leptons and antileptons in the final states, has been extensively searched for in experiments. Taking into account the present experimental limits on muon decays [3], there is really little room remaining for the violation of $L_\mu + L_e$. However, the present upper limits on the branching ratio for rare tau decays provide a possibility of violating $L_e + L_\tau$ or $L_\mu + L_\tau$ at a much higher level.

The Z^0 width measurements at LEP have limited the number of ordinary neutrino species to three with an impressive accuracy. A consistent bound, $N_\nu \lesssim 3.04$ [4], has been derived from studies of big bang nucleosynthesis (BBN) in the early Universe. However, recent analyses [5, 6] show an inconsistency between the standard BBN prediction and observed abundances of primordial ${}^4\text{He}$ and D, and give $N_\nu = 2.1 \pm 0.3$ [6] ruling out $N_\nu = 3$ at 98.6% C.L. To solve the problem one has to conclude that one of the neutrinos, necessarily the tau neutrino, is unstable and, in order not to contribute as one neutrino specie to the BBN, its lifetime τ_{ν_τ} should be limited to

$$\tau_{\nu_\tau} \lesssim 1 \text{ s.} \quad (1)$$

An additional strong requirement arises immediately for the neutrino mass. To avoid its background production via $e^+e^- \rightarrow \bar{\nu}_\tau\nu_\tau$ at BBN time its mass should satisfy $m_{\nu_\tau} \gtrsim \mathcal{O}(1)$ MeV.

In this letter we extend the analyses of Ref. [7] and derive lower bounds on the tau neutrino mass in general $SO(10)$ GUT models taking into account laboratory limits on flavour changing processes and nucleosynthesis results. First we consider the case with $N_\nu = 2$ effective neutrinos contributing to BBN. Later on, we relax the requirement and allow N_ν to be around 3. The obtained bounds depend on the mixing angle of tau neutrino as well as on the bounds on the branching ratio of the process $\tau \rightarrow 3\mu$ and, most strongly, on the mass of new neutral Higgs boson. Therefore, they can be probed through collider experiments and searches for neutrino mixings and other lepton number violating processes.

Among the two maximal continuous subgroups of $SO(10)$, $SU(5)$ and $SU(2)_R \times SU(2)_L \times SU(4)$, which can appear in the symmetry breaking chain, only the latter one is viable phenomenologically. The Pati-Salam gauge group [8] displays the left-right symmetry directly, implying that all quarks and leptons are assigned to left- and right-handed doublets. The Pati-Salam symmetry can break further into the left-right gauge group $SU(2)_R \times SU(2)_L \times U(1)_{B-L}$ which breaks down to the SM. This can be done in several steps, passing through different symmetry groups or in only one step, directly [9].

Concerning the scalar sector, any model should contain at least one representation $\Phi(10)$ necessary to generate Dirac masses for fermions and one representation $\Phi(126)$

necessary to generate Majorana masses for the right-handed neutrinos and give rise to the see-saw mechanism. To avoid arbitrary complications we choose to work with a minimal model containing only one $\Phi(10)$ and one $\Phi(126)$. The $\Phi(10)$ is a complex vector representation of Higgs field whose content under the chiral decomposition is given by

$$10 = (2, 2, 1) + (1, 1, 6).$$

Therefore, derived from a single $\Phi(10)$, there can be one or two Higgs doublets in our low energy theory. Since no unification of $m_b \approx m_\tau$ at the breaking scale of the Pati-Salam subgroup can be achieved with only one doublet [10], only the two doublet models are well motivated in the context of GUT-s. What is relevant for our analyses is that triplet representations, denoted by $\Delta_{R,L}$, exist in both right- and left-handed sectors. They arise from the $\Phi(126)$ representation which decomposes as

$$126 = (1, 1, 6) + (3, 1, \overline{10}) + (1, 3, 10) + (2, 2, 15).$$

The neutral component of the left-handed triplet mediates the non-diagonal neutrino decays which we investigate in this work. As we work with the minimal scalar content, we are going to have only one Δ_L and one Δ_R . However, our results will be unchanged if more scalars would be added.

With this field content the effective Yukawa Lagrangian below the Pati-Salam breaking scale can be written as

$$\begin{aligned} \mathcal{L}_Y = & \overline{\Psi}_L h \phi \Psi_R + \overline{\Psi}_L \tilde{h} \tilde{\phi} \Psi_R + \text{h.c.} \\ & + i \left(\Psi_L^T C \tau_2 \vec{\tau} \cdot f \vec{\Delta}_L \Psi_L + \Psi_R^T C \tau_2 \vec{\tau} \cdot f \vec{\Delta}_R \Psi_R \right) + \text{h.c.}, \end{aligned} \quad (2)$$

where $\Psi_{L,R}$ denote the left- and right-handed lepton doublets, respectively, ϕ a bidoublet of Higgs fields, $\tilde{\phi} = \sigma_2 \phi^* \sigma_2$, and h, \tilde{h} and f are matrices of Yukawa coupling constants in generation space. As required by phenomenology, the vacuum expectation value (vev) $\langle \phi \rangle$ gives masses to the charged leptons (and analogously to quarks) and Dirac masses to the neutrinos, whereas a large $\langle \Delta_R^0 \rangle$ leads to the see-saw mechanism for neutrinos. The vev of the left triplet, $\langle \Delta_L^0 \rangle$, is strongly constrained due to its contribution to the ρ parameter and can be taken to be zero.

Since our purpose is to study the possible degree of $L_e + L_\tau$ or $L_\mu + L_\tau$ violation, we have to discuss experimental constraints on the Yukawa couplings in Eq. (2). The branching ratios of the processes $\mu \rightarrow 3e$ and $\mu \rightarrow \gamma e$ are constrained 5-6 orders of magnitude more stringently than the ones of other flavour changing decays of leptons [3]. It follows from the former process that $f_{e\mu}$ is negligible compared with the other values of f_{ij} and can be neglected [11]. The decay $\mu \rightarrow \gamma e$ sets constraints on the combination $f_{e\tau} f_{\tau\mu}$ of the couplings and imply that one of them can be neglected if the other is assumed to be sizable. Similar argumentation applies also to the Yukawa couplings h_{ij} . Mixing angles of the left-handed neutrinos are given with good accuracy (up to corrections of order $\langle \phi \rangle / \langle \Delta_R \rangle$) by the matrix h , and non-observation of $\mu \rightarrow \gamma e$ constrains the $\nu_e \nu_\mu$ and $\nu_\tau \nu_e$ or $\nu_\tau \nu_\mu$ mixings very strongly. On phenomenological grounds, these constraints are equivalent to imposing the approximate global $U(1)_{\tau+\mu}$ or $U(1)_{\tau+e}$ symmetries¹. We

¹ To be mathematically rigorous, one has to impose an exact global $U(1)$ symmetry and double the number of triplet Higgs multiplets. It was shown in Ref. [7] that for all phenomenological purposes these two approaches are equivalent.

will work with the most natural model with the $U(1)_{\tau+\mu}$ global symmetry and comment later on the implications of imposing the $U(1)_{\tau+e}$. In this limit, the electron generation separates entirely from the μ and τ generations and the decay $\mu \rightarrow 3e$ is forbidden. The Yukawa matrices in Eq.(2) take the form

$$f \equiv \begin{pmatrix} f_{ee} & 0 & 0 \\ 0 & f_{\mu\mu} & f_{\mu\tau} \\ 0 & f_{\tau\mu} & f_{\tau\tau} \end{pmatrix},$$

and similarly for h and \tilde{h} .

The physics we are interested in comes from the left-handed triplet sector of the theory. Since the Δ_L fields do not take part in the Higgs mechanism, we can ignore the couplings of the type $\Delta_L \phi \Delta_R^+ \phi^+$ in the Higgs potential. In this case the Δ_L and Δ_R remain unmixed states. In the basis where all leptons are mass eigenstates the relevant Yukawa Lagrangian is given by

$$\mathcal{L}_Y = \nu_{\mathcal{L}}^T \mathcal{F}' \mathcal{C}^{-\infty} \cdot_{\mathcal{L}} \nu_{\mathcal{L}} + \nu_{\mathcal{L}}^T \mathcal{F}'' \mathcal{C}^{-\infty} \cdot_{\mathcal{L}} \mathcal{L}_{\mathcal{L}} + \mathcal{L}_{\mathcal{L}}^T \mathcal{F} \mathcal{C}^{-\infty} \cdot_{\mathcal{L}}^+ \mathcal{L}_{\mathcal{L}} + \text{h.c.},$$

where $\nu = (\nu_2, \nu_3)$, $L = (\mu, \tau)$ and F , F' and F'' are 2×2 matrices related to each other as $FK^T = F''$, and $KFK^T = F'$. Here K is the leptonic CKM matrix in the left sector involving only the neutrino mixing angle, $\theta_{\mu\tau}$, which can be measured in neutrino oscillation experiments. For large neutrino masses the present limit on the mixing angle is $3 \cdot 10^{-2}$ [3]. Therefore, we denote always $\nu_{2,3} \equiv \nu_{\mu,\tau}$. This bound will be updated, if the angle will not be measured, already this year by CHORUS and NOMAD experiments which have been taking data since 1994 and will achieve the designed sensitivity of $\theta_{\mu\tau} \leq 7 \cdot 10^{-3}$ [12]. The planned Fermilab E803 and NAUSICAA experiments will have the potential to measure also $\theta_{e\tau}$ with the same sensitivity or better, and $\theta_{\mu\tau}$ at the level of 10^{-3} [13].

Our results will explicitly depend on the masses of the left triplet Higgs bosons which are set by some new symmetry breaking scale. However, since Δ_L^0 , Δ_L^+ and Δ_L^{++} belong to the same $SU(2)_L$ multiplet, their mass difference should be of the order of the $SU(2)_L$ breaking scale, i.e., a few hundred GeV at most. Indeed, in the class of $SO(10)$ GUT models what we consider, $M_{\Delta_L^0}$, $M_{\Delta_L^+}$ and $M_{\Delta_L^{++}}$ are not independent. Starting with the most general form of the Higgs potential involving the bidoublet and the triplets one can show that the following relations hold [14]

$$M_{\Delta_L^{++}}^2 = M_{\Delta_L^0}^2 (1 + 2\alpha), \quad M_{\Delta_L^+}^2 = M_{\Delta_L^0}^2 (1 + \alpha),$$

where α is a dimensionless combination of the Higgs potential parameters. Experimentally the values of α can be bounded from the measurements of the parameter $\rho = 1 + \rho_\theta + \rho_\Delta$, where ρ_θ is a correction due to the mixing of Z^0 with a new neutral gauge boson (which we are neglecting here) and ρ_Δ comes from the Δ_L -loop contribution to the Z^0 and W^\pm mass. It is given by [15]

$$\rho_\Delta = \frac{G_F}{4\sqrt{2}\pi^2} [f_{(\Delta_L^0, \Delta_L^+)} + f_{(\Delta_L^+, \Delta_L^{++})}] \equiv \frac{3G_F}{8\sqrt{2}\pi^2} \Delta m^2,$$

where $f_{(x,y)} = M_x^2 + M_y^2 - 2M_x^2 M_y^2 \ln(M_y^2/M_x^2)/(M_y^2 - M_x^2)$. Studies of the new contributions to the ρ parameter have been settled the upper bounds $\Delta m^2 \leq (76 \text{ GeV})^2, (98 \text{ GeV})^2$,

(122 GeV)² [3] for the SM Higgs masses $m_H = 60, 300$ and 1000 GeV, respectively, at 90% C.L. The obtainable lower bounds on α depend strongly on $M_{\Delta_L^0}$ and m_H , and are presented in Table 1. The present mass limit $M_{\Delta_L^0} \gtrsim 45$ GeV, which derives from the LEP invisible Z^0 width measurement, will improve at LEP II and Next Linear Collider (NLC) up to the representative values 80 GeV and 250 GeV, respectively.

Let us now turn to the decays of ν_τ , which can have the following modes

$$\nu_\tau \longrightarrow \nu_\mu \gamma, 3\nu_\mu. \quad (3)$$

The first, the radiative decay mode, is highly suppressed [16] and is not useful in satisfying the constraint (1). Therefore, we are left with the decay $\nu_\tau \rightarrow 3\nu$ mediated by the Δ_L^0 exchange. The effective hamiltonian for this process is given by

$$H = \frac{G_{\nu_\tau}}{\sqrt{2}} \bar{\nu}_\mu \gamma^\lambda (1 - \gamma^5) \nu_\mu \bar{\nu}_\mu \gamma^\lambda (1 - \gamma^5) \nu_\tau + \text{h.c.},$$

where $G_{\nu_\tau} = \sqrt{2} (f_{\mu\mu} + 2\theta_{\mu\tau} f_{\mu\tau}) (f_{\mu\tau} - \theta_{\mu\tau} (f_{\mu\mu} - f_{\tau\tau})) / (4M_{\Delta_L^0}^2)$. The calculation of ν_τ lifetime is straightforward and gives $\tau_{\nu_\tau}^{-1} = 2G_{\nu_\tau}^2 m_{\nu_\tau}^5 / (192\pi^3)$. Using the constraint (1) this yields a lower bound

$$m_{\nu_\tau} \gtrsim \frac{0.11 \text{ MeV} (M_{\Delta_L^0} \text{ GeV}^{-1})^{\frac{4}{5}}}{[(f_{\mu\mu} + 2\theta_{\mu\tau} f_{\mu\tau}) (f_{\mu\tau} - \theta_{\mu\tau} (f_{\mu\mu} - f_{\tau\tau}))]^{\frac{2}{5}}}, \quad (4)$$

which depends explicitly on the bounds on Δ_L^0 mass, $\theta_{\mu\tau}$ and the Yukawa coupling constants f_{ij} . It is important to notice that even if $f_{\mu\tau} = 0$ (i.e, even if there is no $\tau \rightarrow 3\mu$ decay), ν_τ can decay due to the neutrino mixing.

In order to obtain numerical estimates on m_{ν_τ} we have to consider constraints on the triplet Yukawa couplings. Most generally, vacuum stability requires $|f_{ij}| \leq 1.2$ [17], which is also the only available bound on $f_{\tau\tau}$. From the extra contribution to $(g-2)_\mu$ the following bound has been established [11]

$$|f_{\mu\mu}| \lesssim 0.25 \cdot 10^{-2} \sqrt{1 + 2\alpha} \text{ GeV}^{-1} M_{\Delta_L^0}. \quad (5)$$

In the presence of the non-diagonal coupling $f_{\mu\tau}$, the decay $\tau \rightarrow 3\mu$ mediated by Δ_L^{++} , is allowed. Analogously to the previous case, its branching ratio is given by

$$B(\tau \rightarrow 3\mu) = \frac{f_{\mu\mu}^2 f_{\mu\tau}^2}{4\Gamma_\tau M_{\Delta_L^{++}}^4} \frac{m_\tau^5}{192\pi^3},$$

where Γ_τ is the total width of the decaying lepton. The present experimental limit $B(\tau \rightarrow 3\mu) \leq 1.9 \cdot 10^{-6}$ [18] leads to the bound

$$|f_{\mu\mu} f_{\mu\tau}| \lesssim 7.6 \cdot 10^{-8} (1 + 2\alpha) \text{ GeV}^{-2} M_{\Delta_L^0}^2. \quad (6)$$

All these constraints will improve considerably at NLC which will measure the diagonal couplings, including $f_{\tau\tau}$, with the same sensitivity as the off-diagonal ones [19]. To obtain as conservative bounds on the neutrino mass as possible, we have used the maximum

values of α in Table 1 and assumed that the Yukawa coupling constants in Eq. (4) add up constructively. The most stringent constraint appears when the process $\tau \rightarrow 3\mu$ is forbidden and becomes somewhat relaxed if the decay $\tau \rightarrow 3\mu$ is allowed. For the maximally allowed $f_{\mu\tau}$ we obtain

$$m_{\nu_\tau} \gtrsim 9 \text{ MeV}, \quad (7)$$

which is the absolute lower bound on tau neutrino mass in the models we consider. Should CHORUS and NOMAD experiments show negative results, the bound will rise to $m_{\nu_\tau} \gtrsim 14$ MeV.

These are strong constraints, leaving a quite narrow window for the neutrino mass up to the current laboratory limit $m_{\nu_\tau} \lesssim 18$ MeV [20]. On the other hand, a ν_τ in this mass range has important cosmological consequences: it is required by COBE anisotropy measurements to obtain the correct amount of cold dark matter in the Universe [21]. It follows from Eq. (4) that the bounds depend quite weakly on changes in the constraints on τ_{ν_τ} and $\theta_{\nu\tau}$ and relatively strongly on changes of $M_{\Delta_L^0}$. If Δ_L^0 will not be discovered in the running LEP II experiments the bound (7) will rise up to 21 MeV, closing the allowed gap for tau neutrino mass. This would lead into difficulties to understand the BBN result, $N_\nu = 2.1$, in $SO(10)$ GUT-s.

If we relax the constraint (1) and allow the possibility that three neutrinos contribute to BBN, then the tau neutrino, provided its mass exceeds 100 eV, should be unstable and decay via the neutral Higgs exchange at some later time. Most generally, from constraints of the mass density of the Universe [22] one obtains the bound [23, 7]

$$\tau_{\nu_\tau} \leq 8.2 \cdot 10^{31} \text{ MeV}^{-1} \left(\frac{100 \text{ keV}}{m_{\nu_\tau}} \right)^2. \quad (8)$$

More stringent bounds can be derived from considerations of galaxy formation [24] but, as they are model dependent, we are not going to treat them here. It follows from Eq. (8) that

$$m_{\nu_\tau} \gtrsim \frac{3.1 \cdot 10^{-2} \text{ keV} \left(M_{\Delta_L^0} \text{ GeV}^{-1} \right)^{\frac{4}{3}}}{\left[(f_{\mu\mu} + 2\theta_{\mu\tau} f_{\mu\tau}) (f_{\mu\tau} - \theta_{\mu\tau} (f_{\mu\mu} - f_{\tau\tau})) \right]^{\frac{2}{3}}}, \quad (9)$$

implying $m_{\nu_\tau} \gtrsim 48$ keV (which increases up to $m_{\nu_\tau} \gtrsim 102$ keV with the expected CHORUS sensitivity) for the most conservative situation. In this case, recent BBN calculations using the full Boltzmann equation give bounds in the range $m_{\nu_\tau} \lesssim 0.1$ to 0.4 MeV [25] for the Majorana neutrino mass. This range will be tested by LEP II and forthcoming neutrino oscillation experiments or by the NLC (see Table 1) where a sensitivity of $m_{\nu_\tau} \gtrsim 0.5$ MeV will be achieved.

It appears to be difficult to avoid the obtained bounds in $SO(10)$ GUT-s. Enlarging the scalar sector may somewhat increase the effective coupling G_{ν_τ} but, due to the experimental constraints (5) and (6), no sizable effects can be achieved. Since there is no Yukawa couplings to singlets, adding new singlet neutrinos will not open any new decay channels. The possibility of adding new generations with light standard neutrinos is excluded by LEP. Finally, one cannot suppress the triplet Yukawa couplings and force

the right-handed neutrinos to be very light (no see-saw mechanism) since the left-right mixing is known to be negligible and the unique decay mode of ν_τ to three light neutrinos, left- or right-handed, will be strongly suppressed. A possibility to relax somewhat these bounds is to assume that, unlike the situation in quark sector, ν_e and ν_τ are strongly mixed, implying a global $U(1)_{\tau+e}$ symmetry. However, this unnatural situation has a very little breathing space and will become as restrictive as the $U(1)_{\tau+\mu}$ case after the new oscillation data will be available. Certainly, in the case of larger gauge groups, e.g. E_6 , new decay channels occur.

To summarize, in $SO(10)$ GUT-s the BBN result $N_\nu = 2.1$ yields a lower bound 9 MeV (14 MeV if CHORUS and NOMAD experiments will show negative results) on tau neutrino mass. Most importantly, this possibility will be tested in ongoing LEP II experiments. If more than two effective neutrino species contribute to BBN, the presently allowed region for unstable tau neutrino mass, 0.05-0.4 MeV, will be probed by planned neutrino oscillation and collider experiments. The presently allowed mass ranges are of great interest because of their important cosmological consequences.

We are indebted to M.C. Gonzalez-García, C. Jarlskog, K. Kainulainen, E. Roulet, A. Santamaría and J.W.F. Valle for stimulating discussions. G.B. acknowledges the Spanish Ministry of Foreign Affairs for a MUTIS fellowship, whereas M.R. thanks the Spanish Ministry of Education for a post-doctoral fellowship. This work was supported by CICYT, under grant AEN 96/1718.

References

- [1] T. Yanagida, *Prog. Theor. Phys.* **B135** (1978) 66; M. Gell-Mann, P. Ramond and R. Slansky, in *Supergravity*, eds. P. van Nieuwenhuizen and D. Friedman (North Holland, Amsterdam, 1979) p. 315.
- [2] H. Georgi and D. Nanopoulos, *Nucl. Phys.* **B159** (1979) 16.
- [3] R.M. Barnett *et al.*, *Review of Particle Physics*, *Phys. Rev.* **D54** (1996) 1.
- [4] P. Kernan and L. Krauss, *Phys. Rev. Lett.* **72** (1994) 3309.
- [5] K. Olive and G. Steigman, *Phys. Lett.* **B354** (1995) 357.
- [6] N. Hata *et al.*, *Phys. Rev. Lett.* **75** (1995) 3977.
- [7] R.N. Mohapatra, S. Nussinov and X. Zhang, *Phys. Rev.* **D49** (1994) 2410.
- [8] J.C. Pati and A. Salam, *Phys. Rev.* **D10** (1974) 275.
- [9] D. Chang *et al.*, *Phys. Rev.* **D31** (1985) 1718; N.G. Deshpande, E. Keith, and Palash B. Pal, *Phys. Rev.* **D46** (1992) 2261.
- [10] N.G. Deshpande and E. Keith, *Phys. Rev.* **D50** (1994) 3513.
- [11] R.N. Mohapatra, *Phys. Rev.* **D46** (1992) 2990.

- [12] CHORUS Collaboration, D. Macina, in *Proceedings of TAUP 95*, Nucl. Phys. **B** (Proc. Suppl.) **48** (1996) 183; NOMAD Collaboration, M. Laveder, in *Proceedings of TAUP 95*, Nucl. Phys. **B** (Proc. Suppl.) **48** (1996) 188.
- [13] J.J. Gomez-Cadenas and M.C. Gonzalez-Garcia, Z. Phys. **C71** (1996) 443.
- [14] R.N. Mohapatra and P.B. Pal, Phys. Lett. **179B** (1986) 105; N.G. Deshpande, J.F. Gunion, B. Kayser, and F. Olness, Phys. Rev. **D44** (1991) 837.
- [15] P. Herczeg and R.N. Mohapatra, Phys. Rev. Lett. **69** (1992) 2475.
- [16] A. De Rujula and S.L. Glashow, Phys. Rev. Lett. **45** (1980) 942.
- [17] R.N. Mohapatra, Phys. Rev. **D34** (1986) 909.
- [18] ARGUS Collaboration, H. Albrecht *et al.*, Z. Phys. **C55** (1992) 179.
- [19] G. Barenboim, K. Huitu, J. Maalampi, and M. Raidal, Phys. Lett. **B394** (1997) 132; F. Cuypers and M. Raidal, PSI-PR-97-11, FTUV/97-13 (to be published).
- [20] ALEPH Collaboration, L. Passalacqua, in *Proceedings of Fourth International Workshop on Tau Lepton Physics*, Colorado, 1996, <http://tau96.colorado.edu/tau96/ps/Papers.html>, Nucl. Phys. **B** (Proc. Suppl.) (to be published).
- [21] S. Dodelson, G. Gyuk and M. Turner, Phys. Rev. Lett. **72** (1994) 3754; H.B. Kim and J.E. Kim, Nucl. Phys. **B433** (1995) 421; A.S. Joshipura and J.W.F. Valle, Nucl. Phys. **B440** (1995) 647.
- [22] D. Dicus, E. Kolb, and V. Teplitz, Phys. Rev. Lett. **39** (1977) 169.
- [23] E. Kolb and M. Turner, Phys. Rev. Lett. **67** (1991) 5.
- [24] G. Steigman and M. Turner, Nucl. Phys. **B253** (1985) 375.
- [25] M. Kawasaki *et al.*, Nucl. Phys. **B419** (1994) 105; S. Dodelson, G. Gyuk and M. Turner, Phys. Rev. **D49** (1994) 5068; B.D. Fields, K. Kainulainen, and K. Olive, Astropart. Phys. **6** (1997) 169.

$M_{\Delta_L^0}$ (GeV)	α ($m_H=60$ GeV)	α ($m_H=300$ GeV)	α ($m_H = 1$ TeV)
45	5.6	8.4	12.0
80	2.4	3.4	4.8
250	0.56	0.76	1.0

Table 1: Upper bounds on values of α for different triplet and SM Higgs boson masses

Table caption

Table 1. Upper bounds on values of α for different triplet and SM Higgs boson masses