A COSMOLOGICAL UPPER LIMIT ON THE MASS OF HEAVY NEUTRINOS ☆

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An upper limit of 60 GeV is derived on the mass of a stable heavy neutrino, using the standard big bang model This is in addition to the previous limits which constrain the mass of a neutrino to be less than 50 eV or greater than 10 GeV Thus, we predict that in the near future all existing types of stable neutrinos will be detected

By utilizing the cosmological asymmetry of matter over antimatter, it is now possible to set up an upper limit on the mass of a stable neutral lepton Previous works have constrained the mass of such particles to either lie in the range 0–50 eV [1], or be greater than 10 GeV [2,3] allowing the possibility of very heavy neutrinos Here, arguments are given to close the upper window, allowing neutrinos with a mass in the range 10–60 GeV but not substantially higher

At the present time, the Universe contains matter, but hardly any antimatter [4] By conservation of baryon number, the quantity $\eta = (n_B - n_{\bar{B}})/n_\gamma \approx$ $\approx 10^{-9\pm1}$ has remained constant throughout most of the history of the Universe [5] Here, n_B and $n_{\bar{B}}$ are the number densities of baryons and antibaryons, respectively, and n_γ is the number density of photons The limits on η are derived from the following argument [4] The photon number density is obtained from the 3 K background radiation using

$$n_\gamma = 3\,7\, aT^3/k\,, \tag{1}$$

a being the black-body constant

The baryon number density is

$$n_B = \rho_B/m_p\,, \tag{2}$$

where ρ_B is the matter density of baryons in the Universe and m_p is the proton mass The observational limits on ρ_B are [4]

$$10^{-31}\ \mathrm{g\ cm^{-3}} < \rho_B < 2 \times 10^{-29}\ \mathrm{g\ cm^{-3}} \tag{3}$$

Furthermore, all observations point towards $n_{\bar{B}} = 0$ [4] One of the outstanding problems in cosmology is to give an explanation for the observed value $\eta \approx 10^{-9}$

We will argue now that $\eta' \approx \eta$, where $\eta' = (n_\ell - n_{\bar{\ell}})/n_\gamma$, and n_ℓ ($n_{\bar{\ell}}$) is the number density of a conserved lepton (antilepton) type (We assume that the neutrino will be the lightest member of a given multiplet If this were not the case, the lightest charged lepton would be as abundant as electrons in atoms) If $\eta' = 0$, there are no cosmological restrictions for a mass above 10 GeV [3] The neutrinos will have annihilated to such an extent that their abundance at the present time would be too small to conflict with the observations But if the lepton asymmetry is of the same order as the baryon asymmetry, i e $\eta' \approx \eta$, the number of neutrinos left over from the big bang will roughly equal the number of baryons Therefore, a high mass for these neutrinos gives a high matter density in the present Universe, which is restricted by the observations

We offer two arguments which will lead to the desired asymmetry in lepton number First, it is possible that the Universe started off with a non-zero value of η

☆ This paper originated during the Summer School on Physical Cosmology at Les Houches (2–27 July, 1979) as an initial condition The simplest assumption would then be that for all types of particles the relative excess of particles over antiparticles is the same, leading to $\eta' \approx \eta$ There are two possibilities either η was already that small in the beginning, or was unity (no antimatter at all) In the second case, the large number of photons could have been produced by the damping of initial inhomogeneities and anisotropies [6]

A stronger and more appealing argument is based on the recent Grand Unified Theories of strong, electromagnetic and weak interactions (GUT's) [7,8] Just as GUT's produce an asymmetry in the baryon number (possibly of the same order as the observed asymmetry [8,9]), they will produce a comparable lepton asymmetry, $\eta' \approx \eta$ Thus the desired excess may be a consequence of the particle physics in the very early Universe

In order to understand the GUT production of such an asymmetry, it is necessary to consider interactions that violate lepton number conservation As an example of a GUT model, we choose to work with the SU (5) model of Georgi and Glashow [10] However, we expect a similar asymmetry to arise in other grand unified models as well In the SU(5) model the neutrino is placed in a single multiplet together with its corresponding charged lepton and a lower antiquark triplet, thus forming a fundamental $\bar{5}$ representation For example, ν_e is placed in a single multiplet together with e^- and $\bar{d}_R, \bar{d}_y, \bar{d}_B$

$$\begin{pmatrix} \bar{d}_R \\ \bar{d}_y \\ \bar{d}_B \\ e^- \\ \nu_e \end{pmatrix}_L$$

The mixing of members in a given multiplet is governed by an exchange of the superheavy gauge boson triplets X and Y

The interactions which violate lepton number are primarily the decays of the X and Y bosons (X, Y and Higgs mediated collisions seem to be of less importance in producing the desired asymmetry) The X boson decays into two channels, while the Y boson decays into three channels, three of these five violate lepton number conservation These five decays are represented in fig 1 The decays of figs 1b, c, e, each change the lepton number by $\Delta l = -1$

To determine the magnitude of the asymmetry produced by X and Y decays we compare Δl to ΔB

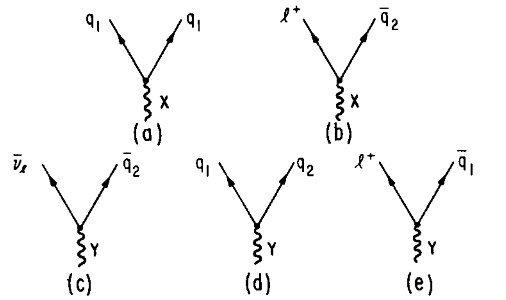

Fig 1 The decay modes for the X and Y bosons where q_1 and q_2 are the upper and lower quarks of the doublet $\binom{q_1}{q_2}$ belongin to the same generation as the lepton ℓ and the massive neutrino

(the asymmetry in baryon number produced by X and Y decays) It is important to note, that in order to produce a lepton asymmetry in the early Universe, three conditions must be satisfied (1) l-conservation violatin interactions, (2) C and CP violation, (3) departure from thermal equilibrium The arguments describing the necessity of these conditions and of their probable simultaneous existence in almost any GUT operating in the early Universe have been discussed in detail in a number of papers [8,9,11] and need not to be restate here We will only remark that since these conditions were satisfied in the early Universe, the asymmetry in the decay rates of X and $\bar{X}$ (Y and $\bar{Y}$) will result in an asymmetry in the lepton production

It should be stressed that the mass of the neutrinos is unimportant at this point as they only receive their mass upon the breaking of the SU(3) × SU(2) × U(1) symmetry, in the hierarchy of the SU(5) symmetry breaking The same also holds true in higher GUT models Thus the only quantities which will affect the interaction rates are the masses of the X and Y bosons (whic are equal) and the temperature of the Universe In general these rates are given by

$$\Gamma_d \sim \alpha m^2_{X,Y} / [(kT)^2 + m^2_{X,Y}]^{1/2} \quad \text{for decays}\,, \quad (4a)$$

and

$$\Gamma_c \sim \alpha^2 (kT)^5 / [(kT)^2 + m^2_{X,Y}]^2 \quad \text{for collisions}\,, \quad (4b)$$

where α is the grand unified coupling

We find that the asymmetry in the lepton number compared to the asymmetry in baryon number produced by X and Y decays is roughly

$$\Delta l \approx \Delta B \ , \tag{5}$$

thus producing more leptons than antileptons A similar situation arises when one examines the X, Y and Higgs mediated collisions Thus given the uncertainty in the ratio $\eta = n_B/n_\gamma$ we can safely state that

$$\eta' = n_\ell/n_\gamma \sim 10^{-9\pm1} \tag{6}$$

Although we have used SU(5) as an example, similar results for the value of η' should be obtained in other GUT models as well Thus we see $\eta' \approx \eta$ can either be postulated as an initial condition for the Universe, or be calculated using the particle physics of the very early Universe We are now in a position to place upper limits on the neutrino mass [‡1]

As shown by Gunn et al [3], heavy neutrinos and matter will collect together to form clusters of galaxies Therefore the total mass density in neutrinos cannot exceed the upper limit ρ_{max} on the mass density observed in clusters of galaxies, $\rho_{max} = 10^{-30}$ g cm^{-3} [12] Thus, we have

$$m_\nu n_\nu = m_\nu \eta' \, n_\gamma < \rho_{max} \ ,$$

or

$$m_\nu < \rho_{max}/\eta' n_\gamma \approx 4 \, \rho_{max}/\eta n_\gamma \tag{7}$$

The factor of four is due to the fact that the three (nearly) massless neutrinos ν_e, ν_μ and ν_τ will be formed in addition to the heavy neutrino, thus one heavy neutrino is produced for every four baryons Using a lower limit for η, $\eta \geqslant 10^{-10}$ [4] we obtain from eq (7) an upper limit on m_ν

$$m_\nu \lesssim 60 \text{ GeV} \tag{8}$$

Note this limit is very sensitive to the uncertainties in the value of ρ_{max}

In summary, we conclude on the basis of the standard big bang model and the universality of the matter–antimatter asymmetry, that neutrinos are only allowed in two small windows out of the total mass spectrum We have also shown that this asymmetry arises naturally as a consequence of Grand Unified Theories It seems plausible that in the near future the energy available in particle accelerators will be high enough to reach the cosmological upper limit on neutrino masses This would mean that all types of stable neutrinos may be detected soon Further work including more detailed calculations and astrophysical implications is in progress [‡2]

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‡1 The neutrino mass can be generated by a suitable choice of Higgs bosons

‡2 In the final preparation of this letter, we noticed a preprint by Nanopoulos et al [13], in which they find a comparable result for $\Delta l/\Delta B$

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