COSMOLOGICAL CONSTRAINTS ON NEUTRINO PHYSICS

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I will briefly comment on the particle physics implications of the two classic constraints on neutrino mass and neutrino counting that arise from cosmological considerations. I show that (i) neutrinos can have any mass allowed by laboratory experiments, in models with spontaneous violation of lepton number, and (ii) nucleosynthesis limits on a new gauge boson may be more stringent than laboratory limits, although crucially dependent on the neutrino mass spectrum. Additional discussion and references may be found in ref. [1].

INTRODUCTION

As we have been just reminded of, our present description of the evolution of the universe in terms of the hot Big Bang cosmological model works very well, at least as far back as the epoch of primordial nucleosynthesis, at $t \sim 10^{-2} sec$ or $T \sim 10\ MeV$. Since neutrinos were very abundant in the early universe, their properties may substantially affect the history and present structure of the universe. Thus one can use this knowledge in order to constrain neutrino properties, such as neutrino masses and lifetimes, as well as the number of neutrino species. Such constraints nicely complement those that can be obtained directly from the laboratory and provide important restrictions on particle physics models.

RELIC NEUTRINO STABILITY

Light neutrinos are cosmologically *stable* if they only have $SU(2) \otimes U(1)$ gauge interactions. Their contribution to the present density of the universe implies [2]

$$\sum_i \frac{g_i}{2} m_{\nu_i} \leq 97\, \Omega_\nu h^2\, eV\ , \qquad (1)$$

where the multiplicity factor $g_i = 2$ if neutrinos are Majorana particles. The sum in eq. (1) runs over all isodoublet neutrino species with mass less than $O(1\ MeV)$. Here $\Omega_\nu = \rho_\nu / \rho_c$ is the ratio of the neutrino density to the critical density, while the constant h^2 measures the uncertainty in the determination of the present value of the Hubble parameter, $0.4 \leq h \leq 1$. Since the product $\Omega_\nu h^2$ is known to be smaller than 1, eq. (1) represents a stringent bound on *stable* neutrino masses. For the case of ν_μ and ν_τ this bound is much stronger than all existing laboratory limits.

Fast neutrino decay (or annihilation [3]) channels could eliminate relic neutrinos and therefore allow neutrinos of higher mass, provided the lifetime obeys

$$\tau \lesssim 1.5 \times 10^7 (KeV/m_{\nu'})^2 yr\ . \qquad (2)$$

This constraint follows from demanding an adequate redshift of the heavy neutrino decay products and holds for neutrinos with $m_{\nu'} < O(1 MeV)$. For heavier neutrinos, such as possible for the case of ν_τ, the cosmological limit on the lifetime is less stringent than that given in eq. (2), due to Boltzmann suppression.

Within the simplest versions of the $SU(2) \otimes U(1)$ theory with massive neutrinos the only decay modes available for neutrinos are radiative decays, such as

$$\nu' \to \nu + \gamma \qquad (3)$$

and, for heavier neutrinos,

$$\nu' \to e^+ e^- \nu. \qquad (4)$$

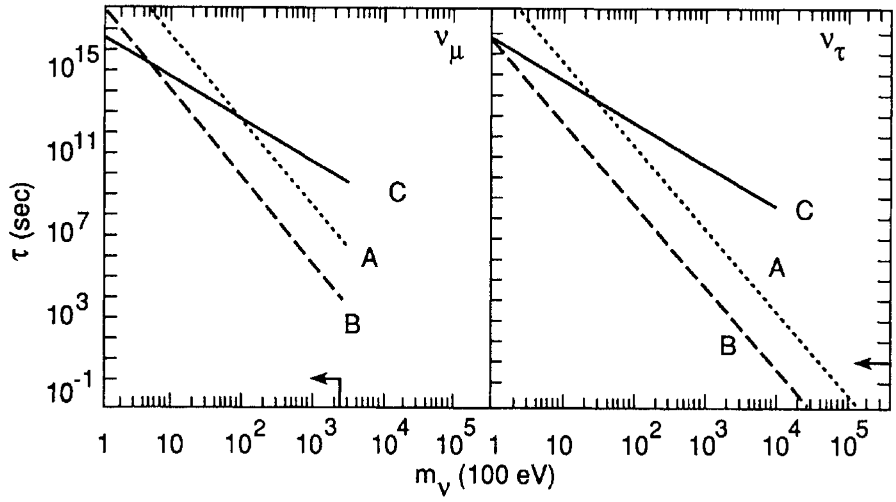

Fig. 1

Typical neutrino decay lifetime versus mass relationship estimated in two versions of the seesaw Majoron model.

However, if the only modes of neutrino decay are *visible*, such as above, it is not possible to lift the cosmological restrictions on neutrino mass, eq. (1), without running into conflict with observation. For example, photons from neutrino decay could dissociate light primordially produced nuclei, as well as produce distortions in the cosmic background radiation spectrum. In addition, there are constraints that follow from the SN87A, as well as from various laboratory experiments [4].

Long ago we noted that the presence of isosinglet neutral heavy leptons (NHLS) in the standard electroweak theory leads to a neutral-current-mediated *invisible* decay mode [5, 6]

$$\nu' \rightarrow 3\nu \qquad (5)$$

In contrast to *visible* decays, decays such as eq. (5) are almost unconstrained, except by the cosmological bound, eq. (2), and possibly by some circumventable arguments related to structure formation. However, this 3ν decay mode would be efficient only for relatively heavy neutrinos, of mass $m_{\nu'} \gtrsim 40\ KeV$. In practice, in the simplest seesaw models *, the decay lifetimes are not sufficiently fast, due to the smallness of the relevant coupling dictated by its relationship with the neutrino mass. On the other hand, for heavier neutrinos obeying $m_{\nu'} \gtrsim 1\ MeV$, this decay would be accompanied by a substantial *visible* component $\nu' \rightarrow e^+e^-\nu$ and, to this extent, one runs again into difficulties when trying to satisfy all of the observational constraints, including the non- observation of a γ-ray burst from SN87A.

*There are models where the 3ν decay mode may be efficient for neutrinos of mass above $200\ KeV$ [7].

The possible existence of non-standard interactions of neutrinos, due to their couplings to electrically neutral spin zero particles brings in the possibility of much faster invisible decays. These are naturally present in models where lepton number symmetry is broken in a spontaneous way, so that there is a Majoron [8]. In these models neutrinos decay via Majoron emission

$$\nu' \rightarrow \nu + J \qquad (6)$$

These 2-body decays can be much faster than the neutral-current-mediated neutrino decay in eq. (5). A detailed study of the rates for the decay $\nu' \rightarrow \nu + J$ was given in ref. [6]. Although in the originally proposed seesaw Majoron model the decays are very much suppressed [6], *beyond* what the naive estimate [8] would suggest, with *light* ($m_{\nu'} \lesssim 20 KeV$) neutrino decay lifetimes *larger* than the age of the universe [6], this is *not* in general so, as illustrated in fig. 1

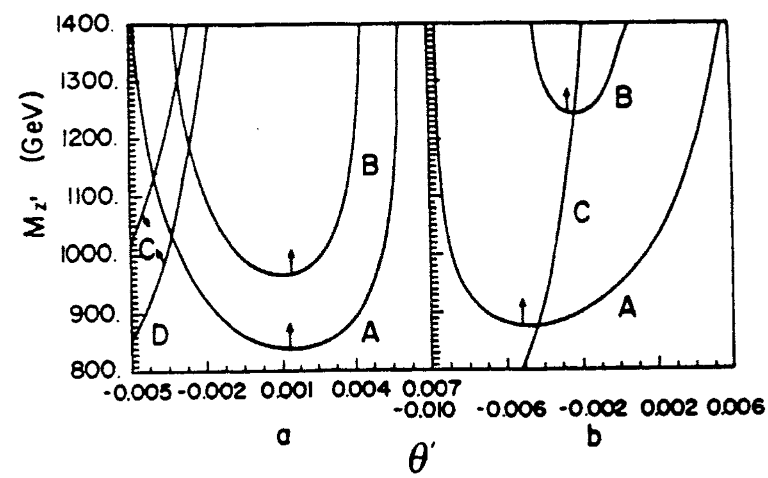

Fig. 2

Nucleosynthesis lower limits on the Z' mass plotted as a function of the $Z - Z'$ mixing angle in superstring inspired E_6 models.

The figure shows how model dependent are neutrino decay lifetimes. Lines A and B give the lifetimes in the simplest seesaw model and in a simple variant model suggested in ref. [9], respectively. All of these models contain NHLS. In case (A) the assumed NHL mass is $M_{NHL} = 50\,GeV$, while in case (B) it is $M_{NHL} = 10\,GeV$ †. Line C denotes the cosmological constraint. All neutrino mass values consistent with laboratory experiments are cosmologically acceptable in model (B). Alternative ways to enhance neutrino decay rates have been discussed in ref. [11]. In these models again the decay of eq. (6) is very efficient, for a wide range of the parameters.

In short, there are many ways to make the decay lifetime of neutrinos sufficiently short as to satisfy the cosmological constraint following from the critical density argument. *In these models neutrinos can have any mass allowed by laboratory experiments.* From this point of view it is rather important to keep improving the laboratory limits on neutrino masses. I look forward to the possibility of a high intensity τ factory (10^7 τ's or more) where one could probe m_{ν_τ} to within $\sim 5\,MeV$ [12]. It is interesting to note that a recent experiment reports evidence for a neutrino mass of $\sim 17\,KeV$ from the β spectra of tritium and ^{35}S [13]. If such an observation were confirmed one might, perhaps, take it as an indication of the existence of the Majoron [14]. Fast invisible neutrino decays may also have other astrophysical and cosmological implications, in connection with the solar neutrino [15] and the dark matter problems [16].

† For these masses one may have NHL signals from Z decays at LEP [3, 10].

NUCLEOSYNTHESIS CONSTRAINTS

The number of neutrino flavours is also restricted by cosmological considerations. The existence of additional weakly interacting light particles, such as neutrinos, could substantially increase the abundance of primordially produced ^4He. This argument leads to the following limit [17]

$$\delta N_\nu \leq 0.4\,, \qquad (7)$$

on the "effective" number of additional neutrinos, assuming that the ν_τ is light enough to be counted just as ν_e or ν_μ. Eq. (7) is the result of the most recent update of the astrophysical analysis discussed here by Schramm [17]. This bound is subject to uncertainties associated with the ν_τ mass, as well as with the input values of the parameters that go into the nucleosynthesis code, as discussed in ref. [18]. For illustration, however, I will take eq. (7) at face value and convert it into a restriction on particle physics models. These involve many exten-

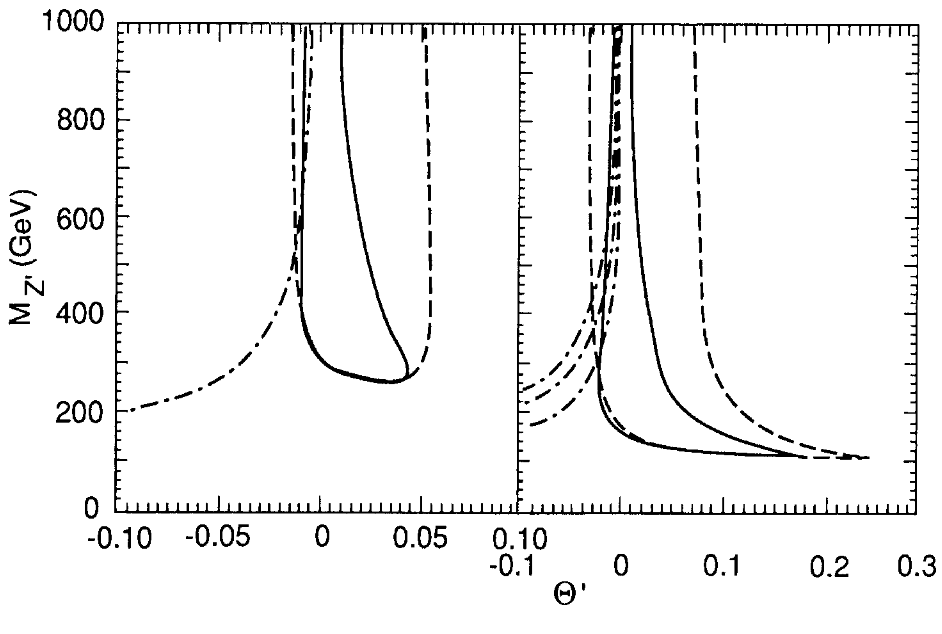

Fig. 3

Regions allowed by laboratory experiments, at 90 % CL, for the mass and mixing of a new neutral superstring inspired E_6 gauge boson, plotted for a top and Higgs mass of 100 GeV. On the left is the χ model and on the right is the η model.

sions of the standard model, that predict the existence of new fermions, such as right-handed neutrinos, lighter than $O(1\ MeV)$, coupled to a new light neutral gauge boson. These additional neutrinos are not completely *sterile*, but couple to ordinary matter with a strength determined by the mass of the new Z'. Such neutrinos are constrained by eq. (7) and one can avoid conflict with the standard Big Bang Nucleosynthesis model only to the extent that the new neutrinos interact *superweakly*, so that they will not keep up with the expansion rate of the universe, due to their early decoupling. Under these circumstances, their implied contribution to the *effective* number degrees of freedom is suppressed, relative to that of the fully *active* left-handed neutrinos. This requirement may be translated into a limit on the mass and mixing of the new gauge boson Z' [19], shown in fig. 2. In one model (η model, left) we have assumed that $N_R = 3$ generations of sequential right-handed neutrinos are lighter than $O(1\ MeV)$. The different curves correspond to different numbers of assumed additional light neutrinos, *i.e.*, $\delta N = 1$ (curve A) and $\delta N = 0.5$ (curve B), for comparison. Region C gives the restriction coming from the diagonalization of the gauge boson mass matrix.

Fig. 2 (right) gives the same information for the superstring inspired χ model. The restriction coming from the diagonalization of the gauge boson mass matrix in this model gives just a curve, labelled C. In this case we have assumed $N_R = 2$ generations of sequential right-handed neutrinos lighter than $O(1\ MeV)$. These nucleosynthesis bounds on string models are *stronger* than the laboratory ones, shown in fig. 3, taken from ref. [20].

However, they could be relaxed if some mechanism exists to decouple some of the right-handed neutrinos, such as present in the χ model of ref. [21], where one of the ν_R's decouples by pairing off with the new heavy gaugino, and acquiring a large mass. This is why we assumed only $N_R = 2$ in fig. 2 (b). In this case we have a weaker Z' mass limit than the one one would have if *all* of the ν_R's were light. Clearly, the nucleosynthesis limits would disappear altogether if all of the new isosinglet leptons could be made sufficiently massive [22], a possibility in general not available in superstring models.

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