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Charged lepton mixing and oscillations from neutrino mixing in the early Universe

D. Boyanovsky *, C.M. Ho

Department of Physics and Astronomy, University of Pittsburgh, 3941 O'Hara Street, Pittsburgh, PA 15260, USA

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Abstract

Charged lepton mixing as a consequence of neutrino mixing is studied for two generations e, μ in the temperature regime $m_\mu \ll T \ll M_W$ in the early Universe. We state the general criteria for charged lepton mixing, critically reexamine aspects of neutrino equilibration and provide arguments to suggest that neutrinos may equilibrate as mass eigenstates in the temperature regime *prior* to flavor equalization. We assume this to be the case, and that neutrino mass eigenstates are in equilibrium with different chemical potentials. Charged lepton self-energies are obtained to leading order in the electromagnetic and weak interactions. The upper bounds on the neutrino asymmetry parameters from CMB and BBN without oscillations, combined with the fit to the solar and KamLAND data for the neutrino mixing angle, suggest that for the two generation case there is resonant *charged lepton* mixing in the temperature range $T \sim 5$ GeV. In this range the charged lepton oscillation frequency is of the same order as the electromagnetic damping rate.

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1. Introduction

Neutrinos play a fundamental role in cosmology and astrophysics [1], and there is now indisputable experimental confirmation that neutrinos are massive and that different flavors of neutrinos mix and oscillate [2–7], thus providing evidence for *new physics* beyond the Standard Model. Neutrino oscillations in extreme conditions of temperature and density are an important aspect of Big Bang Nucleosynthesis (BBN), in the generation of the lepton asymmetry in the early Universe [8,9,5,1,10], and in the physics of core collapse supernovae [11,2].

An important aspect of neutrino oscillations is lepton number violation, leading to the suggestion that leptogenesis can be a main ingredient in an explanation of the cosmological baryon asymmetry [12]. Early studies of neutrino propagation in hot and dense media focused on the neutrino dispersion relations and damping rates in the temperature regime relevant for stellar evolution or big bang nucleosynthesis [13,9,1]. This work has been extended to include leptons, neutrinos and nucleons in the medium [14]. Matter effects of neutrino oscillations in the early universe were investigated in [15,16] and more recently a field theoretical description of mixing and oscillations in real time has been provided in Ref. [17]. While there is a large body of work on the study of neutrino mixing in hot and dense environments, much less attention has been given to the possibility of mixing and oscillation of *charged leptons*. Charged lepton number non-conserving processes, such as $\mu \rightarrow e\gamma$; $\mu \rightarrow 3e$ mediated by massive mixed neutrinos have been studied in the vacuum in Refs. [18–20]. For Dirac neutrinos the transition probabilities for these processes are suppressed by a factor m_a^4/M_W^4 [18–20]. The

* Corresponding author. Tel.: +1 412 624 9037; fax: +1 412 624 9163.
E-mail addresses: boyan@pitt.edu (D. Boyanovsky), cmho@phyast.pitt.edu (C.M. Ho).

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WMAP [21] bound on the neutrino masses $m_a < 1$ eV yields typical branching ratios for these processes $B \lesssim 10^{-41}$ making them all but experimentally unobservable. In this article we explore the possibility of *charged lepton mixing* in the early Universe at high temperature and density. In Section 2 we discuss the general arguments for charged lepton mixing as a result of neutrino mixing and establish the necessary conditions for this mixing to be substantial. We suggest that large neutrino chemical potentials may lead to substantial charged lepton mixing.

Without oscillations BBN and CMB provide a stringent constraint on the neutrino chemical potentials [22,23] ξ_α, with $-0.01 \leqslant \xi_e \leqslant 0.22$, $|\xi_{\mu,\tau}| \leqslant 2.6$. Detailed studies [8,24–27] show that oscillations and self-synchronization lead to flavor equilibration before BBN, beginning at a temperature $T \sim 30$ MeV [25] with complete flavor equilibration among the chemical potentials at $T \sim 2$ MeV [24,25]. Thus *prior to flavor equalization* for $T > 30$ MeV there *could* be large neutrino asymmetries consistent with the BBN and CMB bounds in the absence of oscillations. We study whether this possibility could lead to charged lepton mixing focusing on two flavors of Dirac neutrinos corresponding to e, μ and for simplicity in the temperature regime where both are ultrarelativistic, with $m_\mu \ll T \ll M_W$. In Section 3 we discuss general arguments within the realm of reliability of perturbation theory suggesting that the equilibrium state is described by a density matrix nearly diagonal in the mass basis. In this Section we also discuss caveats and subtleties in the kinetic approach to neutrino equilibration in the literature and argue that results on the equilibrium state are in agreement with the interpretation of an equilibrium density matrix diagonal in the mass basis. Our *main and only assumption* is that for $T > 30$ MeV neutrinos are in equilibrium and the density matrix is nearly diagonal in the mass basis, with distribution functions of mass eigenstates that feature different and large chemical potentials. While this is not the *only*, it is *one* possible scenario for substantial charged lepton mixing that can be explored systematically. In Section 4 we explore charged lepton mixing in lowest order in perturbation theory as a consequence of large asymmetries in the equilibrium distribution functions of mass eigenstates. In this Section we also critically discuss possible caveats and suggest a program to include non-perturbative corrections in a systematic expansion. In Section 5 we summarize the main aspects and results of the article.

2. Charged lepton mixing: the general argument

Charged lepton mixing is a consequence of neutrino mixing in the charged current contribution to the charged lepton self energy. This can be seen as follows: consider the one-loop self energy for the charged leptons. The off-diagonal self-energy $\Sigma_{e\mu}$ is depicted in Fig. 1 for the case of electron-muon mixing. The internal line in Fig. 1(a) is a neutrino propagator off-diagonal in the flavor basis,

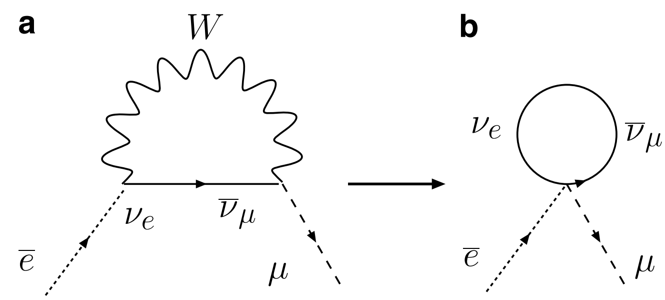

Fig. 1. Off diagonal charged lepton self energy: (a) one loop W-boson exchange and (b) self-energy in the effective Fermi theory.

which is non-vanishing if neutrinos mix. In Fermi's effective field theory obtained by integrating out the vector bosons the effective interaction that gives rise to charged lepton mixing is

$$H_{\mathrm{eff}} = \frac{2G_{\mathrm{F}}}{\sqrt{2}}[\bar{e}_{\mathrm{L}}\gamma_\mu \nu_{e\mathrm{L}}][\bar{\nu}_{\mu\mathrm{L}}\gamma_\mu \mu_{\mathrm{L}}]. \tag{1}$$

A simple Hartree-like factorization yields

$$\frac{2G_{\mathrm{F}}}{\sqrt{2}}\bar{e}_{\mathrm{L}}\gamma_\mu\langle \nu_{e\mathrm{L}}\bar{\nu}_{\mu\mathrm{L}}\rangle\gamma^\mu\mu_{\mathrm{L}} \equiv \bar{e}_{\mathrm{L}}\Sigma_{e\mu}\mu_{\mathrm{L}}, \tag{2}$$

where the brackets stand for average in the density matrix of the system. Eq. (2) gives the charged-lepton mixing part of the self energy as

$$\Sigma_{e\mu} = \frac{2G_{\mathrm{F}}}{\sqrt{2}}\gamma^\mu\langle \nu_{e\mathrm{L}}\bar{\nu}_{\mu\mathrm{L}}\rangle\gamma_\mu. \tag{3}$$

The Fermi effective field theory contribution to the self-energy is depicted in Fig. 1(b).

The focus of this article is to study two aspects that emerge from this observation:

- *Mixing:* The propagating modes in the medium are determined by the poles of the full propagator with a self-energy that includes radiative corrections in the medium. The full self-energy for the charged leptons is a 2×2 matrix (in the simple case of two flavors), and Eq. (3) yields the off-diagonal matrix element in the flavor basis. This is precisely the main study in this article: we obtain the charged lepton propagator including radiative corrections in the medium up to one loop in the electromagnetic and weak interactions. Neutrino mixing leads to off diagonal components of the propagator in the charged lepton flavor basis. We find the dispersion relation of the true propagating modes in the medium by diagonalization of the *full* propagator including one loop radiative corrections. The true propagating modes in the medium are *admixtures* of electron and muon states: this is precisely what we identify as *mixing*. The results given by Eqs. (2) and (3) state *quite generally* that electron and muon states are mixed whenever *the neutrino propagator is off-diagonal in the flavor basis*. We highlight that this is *precisely* the condition for *flavor neutrino oscillations* since the propagator yields the tran-