

Time-dependent Lepton Asymmetry with Primordial Magnetic Fields

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If the neutrino are Majorana particles, the neutrino spin flavor precession induced $\Delta L = 2$ processes which could be relevant for leptogenesis depending on the strength of neutrino magnetic moments and magnetic fields. Although the extra galactic magnetic fields is extremely weak at present time (about 10^{-9} Gauss), the primordial magnetic field at the electroweak scale could be strong (of order 10^{17} Gauss). Therefore, at this scale, the effects of the spin flavor precession could not be negligible. Using present limit on neutrino magnetic moments, we show that the lepton asymmetry may be reduced by 50% due to the spin flavor precession induced by strong primordial magnetic fields. In addition, the leptogenesis will have different feature from the standard scenario of leptogenesis, where the lepton asymmetry continues to oscillate even after the electroweak phase transition.

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1. Introduction

Observations indicate that the baryonic matter we are made off is the remanent of a small matter-antimatter asymmetry originated at the early universe[1, 2]. Leptogenesis is a scenario where it is possible to connect the smallness of the light Majorana neutrino masses with a mechanism to generate this matter-antimatter asymmetry. This mechanism requires right-handed Majorana neutrinos that decay out-of-equilibrium. This decay process, combined with non-perturbative anomalous electro-weak processes, can generate the baryon number in the universe [3, 4, 5, 6, 7]. In this model of baryogenesis, it is expected that the lepton asymmetry to be of the same order of magnitude that of the baryon asymmetry, due to sphaleron effects that are relevant for temperature from 10^{12} GeV to 100 GeV [8, 9]. The measurement of the Baryon Asymmetry of the Universe (BAU) through the anisotropies of the cosmic microwave background radiation (CMB) together with other cosmological observations at a very high level of precision have strongly constrained BAU, that is parameterized by the ratio of baryon number to photon number: $\eta_B = N_B/N_\gamma$. Recent analysis [10] implies that

$$\eta_B = (5.8 \pm 0.27) \times 10^{-10}, \quad (1.1)$$

which show that the measurement of baryon asymmetry is achieved with an error less than 5%.

Unfortunately, the lepton asymmetry is not precisely measured as the baryon asymmetry. Recently, an attempt to constraint the lepton asymmetry from WMAP and nucleosynthesis has been done [11]. The following limits on $\eta_L = (N_{\nu_L} - N_{\bar{\nu}_L})/N_\gamma$ have been obtained:

$$-0.071 < \eta_L < 0.054. \quad (1.2)$$

The fact that non diagonal neutrino magnetic moment μ_ν could induce a neutrino-antineutrino transition due to a helicity flip produced by the interaction of μ_ν with an external magnetic field is known since a long time. It has been called Spin-Flavor precession (SFP) effect. This effect was originally used to explain the solar neutrinos deficit [13, 14, 15, 24]. However, after the confirmation of mixing mass explanation by KamLAND [25], the SFP is used as a mechanism to constraint μ_ν [26].

The effect of a primordial magnetic field on baryogenesis have already been studied [44, 45, 46, 44] but it has been done using the standard model anomaly terms which violates $B + L$ quantum numbers and not through SFP process.

In this talk, we consider the implications of the neutrino SFP on $\Delta L = 2$ processes and leptogenesis induced by strong primordial magnetic fields [12]. In section II we briefly review the neutrino spin flavor precession, induced by the primordial magnetic fields. In section III the time dependent magnetic fields at early universe is discussed. The values of neutrino magnetic moments are discussed in section IV. Section V is devoted to study the effect of SFP on a possible lepton asymmetry previously generated. In section VI the effect of SFP on leptogenesis is studied. Finally our conclusions and remarks are given in section VII.

2. Neutrino Spin Flavor Precession

The assumption that neutrino magnetic moment could be an explanation to the deficiency of the solar neutrino flux through Spin Precession effect were exposed by Cisneros more than 40 years

ago [13] and generalized later to the case of Majorana neutrinos [47]. It is well known that left-handed fermion with magnetic moment could be affected by the Spin Precession effect (SP) which induces in presence of magnetic field a transition from left to right handed fermions or inversely [14, 15, 16, 17, 18, 19, 20, 21, 22, 23]. For the Majorana neutrinos the diagonal components of magnetic moments vanish and the off-diagonal components are related by $-\mu_{e\mu} = \mu_{\mu e} \equiv \mu_\nu$ leading to processes violating flavors and lepton number. In order to find the probability of the $\nu_{eL} \rightarrow \nu_{\mu L}^c$ transition, we need to study the evolution of the chiral components of two flavors of neutrinos, which is described by a Schrödinger type equation [16]. Since we are interested at early epochs of the universe ($T \sim 10^{11}$ GeV), we ignore the neutrino masses and the electron-neutron energy densities. Hence, the solution to the Schrödinger type equation [16] with an arbitrary magnetic field is given by

$$P(\nu_{eL} \rightarrow \nu_{\mu L}^c; t) = \sin^2 \left(\int_{t_0}^t \mu_\nu B_\perp(t') dt' \right). \quad (2.1)$$

where $B_\perp(t)$ is the transverse magnetic field strength, t being the time appearing in the Schrödinger equation. This formula is valid for an arbitrary magnetic field profile $B_\perp(t)$. It is important to notice that the SFP will not stop at Electroweak breaking scale but will continue up to our days.

3. Time-dependent magnetic fields at Early Universe

The main constraints on SFP processes are coming from limits on primordial magnetic field at photon decoupling time obtained through observing microwave background radiation [48] which puts a limit on present time magnetic field to be smaller than 3×10^{-9} G [27]. This limit should be translated into the primordial time assuming that the magnetic field evolution is given by

$$B(t) \simeq B(t_i) \left(\frac{a(t_i)}{a(t)} \right)^2, \quad (3.1)$$

where $a(t)$ is the scale factor, assuming Friedman Robertson Walker dynamics for the Universe (for detailed discussion see ref. [29]). This means that the CMB limit on present value of the primordial magnetic field could be roughly translated into a limit of order 10^9 G for the primordial magnetic field at BBN time [28, 29], which correspond to a time of around 100 s after Big Bang. Thus, it is crucial to translate this bound on the primordial magnetic fields at electroweak symmetry breaking scale and up to the scale of right-handed majorana neutrino decoupling (M_1 around 10^{11} GeV), where the leptogenesis process takes place. At these times (which correspond to radiation domination era), the scale factor is given by

$$a(t) \propto t^{1/2}. \quad (3.2)$$

Thus, the bound on magnetic field at electroweak scale is of order 10^{17} G and at M_1 scale is around 10^{27} G. In this respect, we assume that our time-dependent magnetic field between the time associated to the scale of the heavy right-handed Majorana Neutrinos typically given by $M_1 \simeq 10^{11}$ GeV and the time (t_{EPT}), which corresponds to the time when the Electroweak Phase Transition (EPT) occurs, is given by:

$$B(t) \simeq B(t_{EPT}) \frac{t_{EPT}}{t} \quad (3.3)$$

where $B(t_{EPT}) \simeq 10^{17}$ G.

4. Majorana neutrinos and magnetic moment

Clearly from eq. (2.1) and with primordial magnetic fields as described above, to have a significant Spin-Flavour precession effect it is necessary to have magnetic moments for the Majorana neutrinos not too small. Within the Standard Model, the left-handed majorana neutrinos get a magnetic moment through radiative corrections [30, 31, 32, 33, 34]:

$$\mu_\nu \approx 3.2 \times 10^{-19} \left(\frac{m_\nu}{1\text{eV}} \right) \mu_B \quad (4.1)$$

where μ_B is the Bohr magneton. The strongest constraints on μ_{ν_e} come from Reactor experiment as TEXONO [35] or GEMMA experiments [36]:

$$\mu_{\nu_e} \leq 7.4 \times 10^{-11} \mu_B (\text{TEXONO}) \quad (4.2)$$

$$\mu_{\nu_e} \leq 3.2 \times 10^{-11} \mu_B (\text{GEMMA}) \quad (4.3)$$

From solar neutrinos, it is possible to constraint the neutrino magnetic moments. Recently, BOREXINO [38] obtains the following bound:

$$\mu_{\nu_e} \leq 5.8 \times 10^{-11} \mu_B \quad (4.4)$$

For Majorana neutrinos, global fits on neutrino magnetic moments have been done using solar and reactor data and they obtained [37]:

$$\mu_{ij} \leq 2.0 \times 10^{-10} \mu_B \quad (4.5)$$

The experimental limits are far from the expected values for the neutrino magnetic moments as computed within Standard Model. The main difficulty to build models beyond Standard Model with large neutrino magnetic moment is due to the fact that a large magnetic moment is usually related to strong New Physics contribution to neutrino masses but this problems can be solved in many New Physics models where $\mu_{\nu_{ij}}$ as large as $10^{-12} \mu_B$ can be reached even for m_ν smaller than 1 eV [39, 40, 41, 42, 43]. In models beyond the standard model like MSSM, the magnetic moments of neutrinos are enhanced by several order of magnitudes, for example $\mu_{\nu_e} \sim 10^{-15} 10^{-16} \mu_B$, and $\mu_{\nu_\mu} \sim 10^{-12} 10^{-13} \mu_B$, while $\mu_{\nu_\tau} \sim 10^{-12} \mu_B$. Therefore, the neutrino magnetic moments can be a probe for the new physics beyond the standard model. For our numerical estimate of the SFP effects, we shall use the value of $10^{-12} \mu_B$ for the majorana neutrino magnetic moments.

5. Spin Flavor Precession and Lepton asymmetry

We now study the effect of spin-precession process on light, mainly left-handed, majorana neutrino assuming the existence of a time-dependent primordial magnetic fields given in Eq.(3.3). In order to include in the Boltzman equation the terms corresponding to the spin-precession effects, it is important to recall in two flavor case that the variation $\Delta N_{\nu_{1,2}}$ in $\nu_{1,2}$ number density due to SFP is given by

$$\Delta N_{\nu_1} = P(\nu_2^c \rightarrow \nu_1) N_{\nu_2^c} - P(\nu_1 \rightarrow \nu_2^c) N_{\nu_1} \quad (5.1)$$

$$\Delta N_{\nu_2} = P(\nu_1 \rightarrow \nu_2^c) N_{\nu_1} - P(\nu_2^c \rightarrow \nu_1) N_{\nu_2^c} \quad (5.2)$$

where the first term in Eq. (5.1) account for the number of ν_2^c 's which have been changed into ν_1 and the second term is equal to the number of ν_1 's which have been changed into ν_2^c . Similar equations can be built for $\Delta N_{\nu_{1,2}^c}$. Defining the lepton number density as

$$N_L \equiv N_{\nu_1} + N_{\nu_2} - N_{\nu_1^c} - N_{\nu_2^c},$$

and assuming CP is conserved (*i.e.*, $P(\nu_1 \rightarrow \nu_2^c) = P(\nu_1^c \rightarrow \nu_2)$), one gets

$$\Delta N_L = -2PN_L \quad (5.3)$$

where P is the probability of SFP given by Eq. (2.1). This approach can be easily extend to n_f flavors and we obtain

$$\frac{dN_L}{dt} = -2(n_f - 1) \frac{d}{dt} (PN_L). \quad (5.4)$$

This equation represents a new contribution for the lepton asymmetry that will affect the leptogenesis scenario. Thus, the lepton number density $N(t)$ is given by

$$N_L(t) = \frac{N_L^0}{1 + 2(n_f - 1)P(\bar{\nu} \rightarrow \nu)}, \quad (5.5)$$

where N_L^0 is the initial lepton number density. It is clear that for probability $P(\bar{\nu} \rightarrow \nu) \simeq \mathcal{O}(1)$, the lepton asymmetry can be reducing respect to its initial value by a factor $1/5$.

It is worth mentioning that for magnetic fields below $10^{14} G$ and due to limit on the neutrino magnetic moment [26] to be $\mu < 10^{-12} \mu_B$, one can easily check from Eq.(2.1) that the SFP process is irrelevant between the scale of right-handed neutrino decays (t_{M_1}) and electroweak symmetry breaking time (t_{EPT}). So for primordial magnetic field smaller than $10^{14}G$, SFP process will not affect directly the usual leptogenesis scenario. However as it will be shown explicitly below, it will continue to affect the lepton asymmetry even after the electroweak symmetry breaking, transforming it as a time-oscillating function. This is important as in usual leptogenesis scenario, the lepton and baryon asymmetry of the Universe are related through a simple relation which only depends on matter contents of the model. Even with a relatively weak primordial magnetic field (below $10^{14} G$), this relation between η_L and η_B is lost.

6. Leptogenesis and Spin Flavor Precession

Here, we assume a strong primordial time-dependent magnetic field, given by Eq.(3.3), before electroweak phase transition and compatible with present limits on cosmological magnetic fields. In order to get the SFP effects on Leptogenesis standard scenario¹, we solve the Boltzman equation of the heavy right-handed (RH) majorana neutrino, N_1 , that decays violating CP and producing a lepton asymmetry through usual leptogenesis scenario. This lepton asymmetry is transformed into the Baryon Asymmetry of the Universe through anomalous $B + L$ violating sphaleron processes which are in equilibrium between $10^{12} GeV > T > 100 GeV$. For simplicity and in order to clearly see the SFP effects on Boltzman equations, we assume that the $\Delta L = 1$ scattering processes

¹for a detail description of Leptogenesis standard scenario see for instance ref. [7]

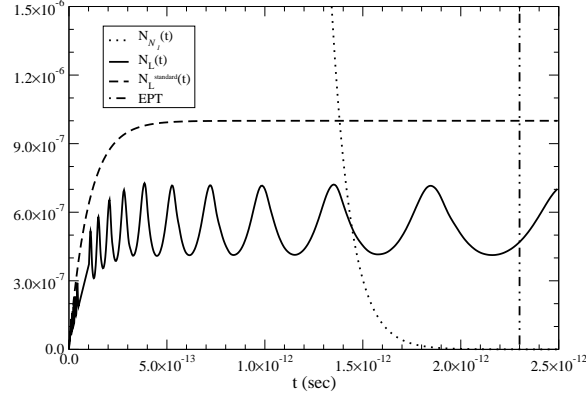


Figure 1: The continue oscillating line corresponds to η_L including SFP effects. The dash line is η_L as expected from standard leptogenesis scenario. The vertical dotted-dash line represents an approximate value for Electroweak Phase Transition Time (t_{EPT}). For $t > t_{EPT}$, the η_L is not anymore converted into η_B through $B + L$ violating sphalerons. The dotted line show the evolution of the heavy RH majorana neutrino density N_1

in Boltzman equation for heavy RH majorana neutrinos are out of equilibrium and that the only relevant terms is the one describing the heavy RH neutrino decays and inverse decays. Also, for the N_L Boltzman equation, we assume that all $\Delta L \neq 0$ processes induced by heavy neutrinos are out of equilibrium and are not able to wash out any produced lepton asymmetry. Within these approximation, the basic equations for leptogenesis including SFP effects are given by

$$\begin{aligned} \frac{dN_{N_1}}{dt} &= -\Gamma_D N_1 \\ \frac{dN_L}{dt} &= \varepsilon \Gamma_D N_{N_1} - 2(n_F - 1) \frac{d(PN_L)}{dt} \end{aligned} \quad (6.1)$$

where Γ_D represent the Direct and Inverse Decay and N_1 is the heavy RH Majorana neutrino density. From [7], we use $\varepsilon = 10^{-6}$ and Γ_D is given by

$$\Gamma_D = \frac{1}{8\pi} \frac{m_1 M_1}{v^2} M_1 \frac{K_1(z)}{K_2(z)}. \quad (6.2)$$

where $K_i(z)$ are the Bessel functions, and m_1 is the effective light neutrino mass, v is the usual electroweak symmetry breaking scale and M_1 is the heavy RH neutrino mass[7]. The results of integrating these equations are shown in Fig 1.

7. Conclusion

We have studied the impact of the neutrino spin flavor precession, induced by coherent primordial magnetic fields, on the lepton asymmetry and leptogenesis process. In order to implement the SFP leptogenesis we assumed a strong primordial magnetic fields and sizeable neutrino magnetic moment in addition to the usual assumptions of standard leptogenesis, required to generate the Baryon Asymmetry of the Universe in particular the wash out processes are out of equilibrium. We have shown that contrary to what could be naively expected from the weakness of the extra and

intra galactic magnetic fields at present time, primordial magnetic fields in Early Universe could be large enough to significantly affect Leptogenesis scenario. With such strong magnetic field at electroweak symmetry breaking time, we have shown that the SFP effects reduce the lepton asymmetry by around a factor 50% and increase the uncertainties on the produced BAU as the uncertainties on the electroweak phase transition time which corresponds to the freezing of the BAU are important. Even for magnetic fields too weak to modify Leptogenesis scenario, their presence induces an oscillating behavior for the lepton asymmetry at later stage in the History of the Universe, leading to lose the relation between Lepton and Baryon asymmetry as usually given in Leptogenesis models. A profile for the magnetic fields up to time around 100 seconds after Big Bang is needed in order to perform more precise numerical. It is also important to stress that the hypothesis of coherent primordial magnetic fields can be easily relaxed once the distribution of the primordial magnetic fields is known. Within this SFP leptogenesis scenario, an important consequence of a no-coherent distribution of primordial magnetic fields is to induce the formation of region of the Universe with different values for the lepton asymmetry.

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