Resonant electromagnetic Leptogenesis

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Brussels, 14/07/2010

I would like to thank Prof. Hambye for the kind invitation

Outline

1. Introduction.
2. Standard leptogenesis scenario.
3. Our Model
   - Brief introduction.
   - Strength of effective EMDM coupling.
   - Resonant electromagnetic leptogenesis.
   - Neutrino mass.
   - Implications of the model.
4. Summary and Conclusion.

Introduction

- Inability of SM to account for established features of our universe such as
  1. Presence of Dark Matter
     and dark energy density of the Universe
  2. Observed nonzero Neutrino mass
  3. Baryon Asymmetry
     Origin of observed asymmetry between particles and antiparticles
  4. Many others...
- Unification of Fundamental Forces is not possible
- Gravity is Completely Left Out

$$\Downarrow$$

Journey to
BEYOND STANDARD MODEL

In this talk, i will discuss only

- the matter-antimatter asymmetry creation via electromagnetic leptogenesis.
- neutrino mass.

Standard leptogenesis scenario

1. In standard leptogenesis scenario, CP and L violating interactions originate from the Yukawa terms in the Lagrangian:

$$\mathcal{L} = -\bar{\ell}_L \, h \, \phi \, N_R - \frac{1}{2} \overline{N_R^c} \, M \, N_R$$

- Yukawa term connects the light and heavy neutrino
- L and CP violating and out of equilibrium decay of N_R gives required asymmetry.

1. First studied in Fukugita and Yanagida' 86.
   - First create an excess of L, and then turn it into an excess of B.

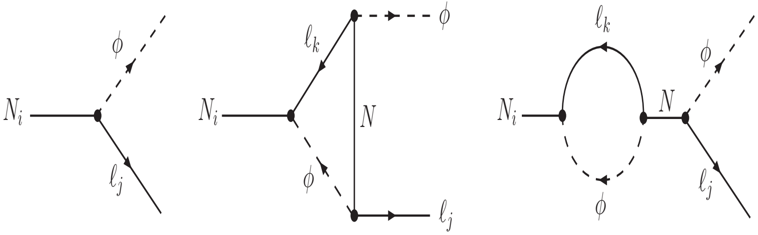


Figure: Feynman diagram gives lowest contribution to decay of right handed Majorana neutrino into a photon and a SM light lepton

2. Creating an excess of L: requires L and CP violating processes that will go out of thermal equilibrium at some stage during the evolution of the Universe (Sakharov's conditions revisited).
   - L and CP violating interactions. $\rightarrow$ Extensions to the SM.
   - thermal non-equilibrium. $\rightarrow$ fast expansion rate H.

Mass bound on M_1

1. For Hierarchal case $M_1 << M_{2,3}$,

   $4\times 10^8 \mathrm{GeV} \leq M_1 \leq 10^{18}\mathrm{GeV}$ $Barbieri'00, Davidson - Ibarra'02$

2. Quasi-degenerate N_i spectrum($M_1 \sim M_2 << M_3$)
   This is called Resonant effect or Leptogenesis scenario is known as resonant leptogenesis.

3. $M_1 \sim 100$ GeV Pascos,Sarkar'96; Pilaftsis'98, Pilaftsis' etal '04..

   Absolute bound on $M_1 > 2.6$ GeV Hambye etal'08; '03.

4. many important studies has been persuaded in this subject which is difficult to cite here.

Motivations for electromagnetic leptogenesis

The question can be asked: is there any other way to find the required lepton asymmetry to explain matter-antimatter asymmetry.

The answer is YES

1. In this work, we wish to explore the possibility of leptogenesis via the decay of heavy neutrino to a photon and a lepton (instead of Higgs and lepton as in standard leptogenesis).

Model

Table: Particle content of the model:

	Field	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Z_2
Fermions	$Q_L \equiv (u, d)_L$	(3, 2, 1/6)	-1
	u_L^c	(3*, 1, -2/3)	+1
	d_L^c	(3*, 1, 1/3)	+1
	$\ell_L \equiv (\nu,\ e)_L$	(1, 2, -1/2)	-1
	e_L^c	(1, 1, 1)	+1
	N_R	(1, 1, 0)	-1
	E_L	(1, 1, -1)	-1
Scalars	Φ	(1, 2, -1/2)	-1
	D	(1, 2, +1/2)	+1
	Σ	(1, 2, +1/2)	+1
	H^+	(1, 1, +1)	+1

1. With this particle content, the Yukawa interactions in our model is as follows

$$\begin{aligned}\mathcal{L} &= \Big[y_H \, \overline{N_R} \, E_L H^+ + y_\Sigma \overline{\ell_L^c} E_L^c \Sigma + y_D \overline{\ell_L^c} E_L^c D \\ &+ h_\Sigma \overline{N_R} \ell_L \Sigma + h_D \overline{N_R} \ell_L D + y_e \bar{\ell}_L \tilde{\Phi} e_L^c + h.c. \Big] \\ &+ M_N \overline{N_R^c} N_R + M_E \overline{E_L^c} E_L \end{aligned} \quad (1)$$

2. The scalar potential is given by

$$\begin{aligned} V(\Phi, \Sigma, D, H^+) &= -\mu_1^2 |\Phi|^2 + \lambda_1 |\Phi|^4 + m_2^2 |\Sigma|^2 + \lambda_2 |\Sigma|^4 \\ &+ \mu_3^2 |D|^2 + \lambda_3 |D|^4 + f_1 |\Phi|^2 |D|^2 + f_2 |\Phi^\dagger D|^2 \\ &+ f_3 |\Phi|^2 |\Sigma|^2 + f_4 |\Phi^\dagger \Sigma|^2 + f_5 |D|^2 |\Sigma|^2 + f_6 |D^\dagger \Sigma|^2 \\ &+ \frac{\lambda_6}{2} \left[(\Phi^\dagger \Sigma)^2 + h.c. \right] + m_h^2 |H|^2 + \lambda_h |H|^4 \\ &+ \left[\mu_s \, \Sigma \cdot D \, (H^+)^* + h.c. \right] . \end{aligned} \quad (2)$$

1. The electromagnetic(EM) couplings between the light and heavy neutrinos through effective operators:

$$\boxed{\frac{1}{M}\bar{\psi}_1 \mu \sigma^{\alpha\beta}\psi_2 F_{\alpha\beta}}, \quad \boxed{\frac{1}{M}\bar{\psi}_1 i d \gamma^5 \sigma^{\alpha\beta}\psi_2 F_{\alpha\beta}}$$

   where λ, d are dimensionless couplings, $F_{\alpha\beta}$ is the electromagnetic field stress tensor and M is the scale of the effective theory.

2. When written in terms of chiral fields, the most general electromagnetic dipole moment (EMDM) coupling of N_R to ν_L is given by

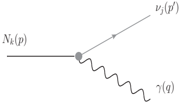
$$\lambda \bar{\nu}_L \sigma^{\alpha\beta} N_R F_{\alpha\beta} \tag{3}$$

1. We begin by considering the dim-5 EMDM term:

$$\boxed{\lambda \bar{\nu}_j \sigma^{\alpha\beta} P_R N_k F_{\alpha\beta} + h.c.}$$

where λ is EMDM coupling of inverse of mass dimension i.e, $\lambda = \frac{\lambda_0}{M}$.

2. Through this, the heavy RH neutrinos can now decay into a light neutrino and a photon in the early universe:-



3. In Kayser etal'08, Out of equilibrium condition is not satisfied??.
   The large value of effective EMDM coupling constant is difficult.
4. This is the another motivation for us to study the electromagnetic leptogenesis

EM leptogenesis scenario(Cont....)

1. The next task is to calculate the CP-asymmetry parameter for this decay

$$\varepsilon_{k,j} \equiv \frac{\Gamma_{(N_k\to\gamma+\nu_j)} - \Gamma_{(N_k\to\gamma+\bar{\nu}_j)}}{\Gamma_{(N_k\to\gamma+\nu_j)} + \Gamma_{(N_k\to\gamma+\bar{\nu}_j)}}$$

2. Interference of the tree level and one loop diagrams required for this calculation.
3. This is possible only if
   - the EMDM coupling matrix λ is complex.
   - the intermediate states of the loop diagrams go on-shell.

Estimation of EMDM coupling λ

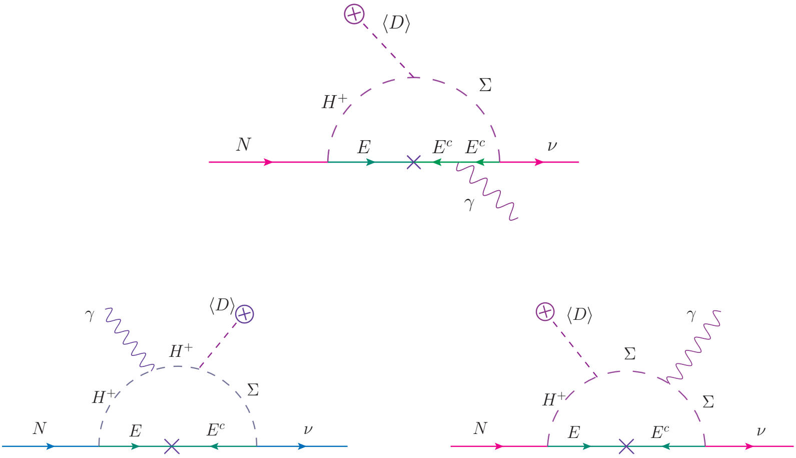


Figure: Feynman diagrams which estimate the effective EMDM coupling strength between light neutrino ν and N.

Strength of EMDM coupling(Cont....)

- The EMDM coupling strength is

$$\lambda = -\frac{e(y_\Sigma^* \, y_H \, \mu_s \, v_d)}{4\,\pi^2\,[M_\Sigma^2 - M_H^2]} \int_0^1 dx \int_0^{1-x} dy \left[\mathcal{I}_1 + \mathcal{I}_2 + \mathcal{I}_3\right]$$

Where $\mathcal{I}_1$, $\mathcal{I}_2$ and $\mathcal{I}_3$ are contribution coming from three diagrams. Assuming $M_E \sim M_\Sigma \sim M_H = M$ are of the order of TeV scale, these integrals are as follows:

$$\mathcal{I}_1 = \int_0^1 dx \int_0^{1-x} dy\,(y-1)[\Omega_1 - \Omega_2].$$

Where

$$\Omega_1 = [(y - y^2 - x\,y)Z_N - y\,Z_S - (1-y)]^{-1},$$
$$\Omega_2 = [(y - y^2 - x\,y)Z_N - y\,Z_H - (1-y)]^{-1},$$

and the parameters in these integrals are: $Z_S = \frac{M_\Sigma^2}{M_E^2}$, $Z_N = \frac{M_N^2}{M_E^2}$, $Z_H = \frac{M_H^2}{M_E^2}$.

- $$\mathcal{I}_2 + \mathcal{I}_3 = 2\left[[B_1^{(0)} - B_1^{(1)} - C_1^{(1)}] - [B_2^{(0)} - B_2^{(1)} - C_2^{(1)}] \right],$$

Where the integral as follows

$$B_1^{(n)} = \int_0^1 dx \int_0^{1-x} dy\, x^n \;\; \omega_1$$
$$C_1^{(n)} = \int_0^1 dx \int_0^{1-x} dy\, y^n \;\; \omega_1$$

and

$$B_2^{(n)} = \int_0^1 dx \int_0^{1-x} dy\, x^n \;\; \omega_2$$
$$C_2^{(n)} = \int_0^1 dx \int_0^{1-x} dy\, y^n \;\; \omega_2$$

Here $\omega_1 = [-y\, Z_S + x(1 - Z_S) - (1 - x - y) - x(x + y) Z_N]^{-1}$
and $\omega_2 = [-y\, Z_S + x(1 - Z_H) - (1 - x - y) - x(x + y) Z_N]^{-1}$

Strength of EMDM coupling(Cont....)

1. Maximal value of the EMDM coupling is

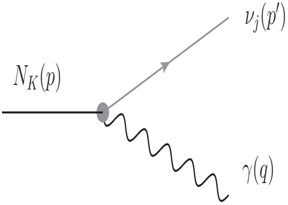
$$\lambda \sim -\frac{e(y_\Sigma^* \, y_H \, \mu_s \, v_d)}{128\,\pi^2\, M_E^3}$$

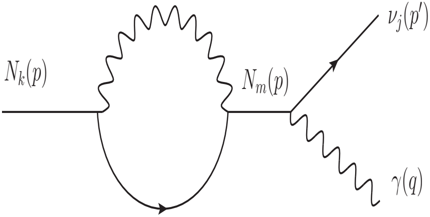
2. For the same sets of parameters: $M_N = 1$ TeV, $M_E \sim M_H \sim M_\Sigma \sim 1000$ GeV, $y_\Sigma = y_H \sim 10^{-1}$, $\mu_s = 100$ GeV and $v_d = 100$ GeV, the EMDM coupling strength which is responsible for electromagnetic leptogenesis is found to be $\sim 10^{-11}$.
3. Which imply the dimensionless coupling is $\lambda_0 \sim 10^{-8}$ as

$$\lambda = \frac{\lambda_0}{M}$$

where M is in TeV range in our model.

Electromagnetic leptogenesis





For two right handed neutrino case, the CP-asymmetry is

$$\varepsilon_1 = -\frac{M_1^2}{2\pi(\lambda^\dagger\lambda)_{12}} \sum_{2\neq 1} \mathrm{Im}\left[(\lambda^\dagger\lambda)_{12}^2\right] \frac{(M_2^2 - M_1^2)M_2^2}{(M_2^2 - M_1^2)^2 + M_1^2\,\Gamma_2^2}$$

Tree level decay rate is

$$\Gamma(N_1 \to \nu\,\gamma) = \frac{(\lambda^\dagger\lambda)_{11}}{4\pi}\, M_1^3$$

Electromagnetic leptogenesis(Cont.....)

1. For resonant condition where

$$|M_2 - M_1| \sim \Gamma_1/2$$

we found maximum CP-asymmetry, i.e, $\varepsilon \sim 1$.

2. We are interested the case where $|M_2 - M_1| >> \Gamma_1/2$.
3. In this case, the expression becomes

$$\varepsilon_1 = -\frac{M_1^2}{2\pi(\lambda^\dagger\lambda)_{12}} \sum_{2\neq 1} \mathrm{Im}\left[(\lambda^\dagger\lambda)_{12}^2\right] \frac{M_1}{|M_2 - M_1|}$$

4. We are interested the case where $|M_2 - M_1| >> \Gamma_1/2$. We need mass splitting of $10^{-9} - 10^{-10}$ to account for $\varepsilon \sim 10^{-5}$ for successful leptogenesis.

Electromagnetic leptogenesis(Cont.....)

1. For successful leptogenesis, the size of the EMDM coupling should be constrained by the out of equilibrium condition. From this the upper bound on the EMDM couplings reads as

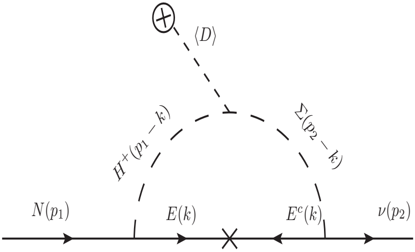
$$\sqrt{\sum_m |\lambda|^2} < 10^{-20} \sqrt{\frac{1}{(M_1/TeV)}}$$

2. In other words, the dimensionless couplings constrained as

$$\sqrt{\sum_m |\lambda_0|^2} < 10^{-14} \sqrt{\frac{1}{(M_1/TeV)}}$$

Neutrino mass:

- The Dirac mass of the neutrino comes from loop diagram given below.



- This Dirac mass term together with the heavy right handed Majorana neutrino mass M can give rise to a light neutrino Majorana mass after diagonalizing the total neutrino mass matrix.

- The analytical expression of Dirac type of neutrino mass is

$$m_D = -\frac{(y_\Sigma^* \, y_H \, \mu_s \, v_d)}{16\,\pi^2 \, M^2} M_E \, \mathcal{I} \tag{4}$$

Where the integral is

$$\mathcal{I} = \int_0^1 dx \int_0^{1-x} dy \Big[[-y\, Z_S + x(1-Z_H) - (1-x-y) - x(x+y)\, Z_N] \Big]^{-1}$$

For the specific case where all mass scales are same, then the integral:

$$\mathcal{I}^{max} = \int_0^1 dx \int_0^{1-x} dy \frac{1}{[x - 1 - x(x+y)]} \sim 1/2$$

and expression for neutrino mass becomes

$$m_D \sim -\frac{(y_\Sigma^* \, y_H \, \mu_s \, v_d)}{32\,\pi^2 \, M_E} \tag{5}$$

Neutrino mass:(Cont.....)

- For the set of parameters: $M_N = 1$ TeV, $M_E \sim M_H \sim M_\Sigma = 1000$ GeV, $y_\Sigma \sim 10^{-1}$, $y_H \sim 10^{-1}$, $\mu_s = 100$ GeV and $v_d = 100$ GeV, the Dirac type neutrino mass is $M_D \sim 10^{-4}$ GeV.
- After diagonalizing, the light neutrino mass matrix becomes

$$m_\nu = m_D M_N^{-1} m_D.$$

- For $M_N \sim$TeV and $M_D \sim 10^{-4}$ calculated from loop diagram, the value of light neutrino mass is found to be 0.05 eV.

Posiible signature of our Model

1. The model can be accessible at LHC(all the particles are at TeV scale).
2. One need to check whether there will be a enhancement of the processes like $H \to \gamma\gamma$.
3. Production of right handed neutrino and corresponding dilepton signature can be found at LHC.

Summary and Conclusion

1. The resonant electromagnetic leptogenesis
   - is in principle a viable alternative for achieving successful leptogenesis.
   - requires the RH neutrino mass scale $\sim 10^3$ GeV.
2. Need to investigate such a new mechanism,like, whether it can significantly alter the standard leptogenesis picture
3. Light neutrino mass of 0.05 eV is possible with the allowed parameters in our model.

Thank You