Effects of Ligthest ν Mass in Leptogenesis

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Summary

1. Introduction
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   - See-Saw Mechanism
2. Flavour Effects in Leptogenesis
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   - CP-Violation in Flavoured Leptogenesis
   - Low Energy CP-Violation
3. Lightest ν Mass Contribution
   - Inverted Ordering $m_3 < m_1 < m_2$
   - Normal Ordering $m_1 < m_2 < m_3$

Observed Baryon Asymmetry (per entropy density): $Y_B \equiv \frac{n_B - n_{\bar{B}}}{s} \cong 8.6 \times 10^{-11}$

E. M., S.T. Petcov, T. Shindou and Y. Takanishi, "Effects of Lightest Neutrino Mass in Leptogenesis", Nucl.Phys.B797:93-116,2008

- We work in the context of "flavoured" thermal leptogenesis.
- In this framework CP-violation necessary for the generation of the observed baryon asymmetry (matter-antimatter) of the Universe can be due exclusively to the Dirac and/or Majorana CP-violating phases in the $U_{\rm PMNS}$ neutrino mixing matrix $\Longrightarrow$ connection between leptogenesis and "low energy" CP-violation in the lepton (neutrino) sector (neutrino oscillations, $(\beta\beta)_{0\nu}$-decay, etc.).

  S. Pascoli, S.T. Petcov, A. Riotto, Phys. Rev. D75 083511 (2007)

  S. Pascoli, S.T. Petcov, A. Riotto, Nucl. Phys. B 739 (2006) 208
- The case of inverted hierarchical light ν mass spectrum is investigated in detail.

Type I See-Saw Scenario and Leptogenesis

$$\mathcal{L}^{\rm lep}(x) = \mathcal{L}_{\rm CC}(x) + \mathcal{L}_{\rm Y}(x) + \mathcal{L}_{\rm M}^{\rm N}(x)$$

$$\begin{aligned}
\mathcal{L}_{\rm CC}(x) &= -\frac{g}{\sqrt{2}}\overline{\ell_L}(x)\,\gamma_\alpha\,\nu_{\ell L}(x)\,W^{\alpha\dagger}(x) + \text{h.c.} \\
\mathcal{L}_{\rm Y}(x) &= \lambda_{i\ell}\,\overline{N_i}(x)\,H^\dagger(x)\,\psi_{\ell L}(x) + h_\ell\,H^c(x)\,\overline{\ell_R}(x)\,\psi_{\ell L}(x) + \text{h.c.} \\
\mathcal{L}_{\rm M}^{\rm N}(x) &= -\frac{1}{2}\,M_i\,\overline{N_i}(x)\,N_i(x)\,, \qquad i = 1,2,3
\end{aligned}$$

- At energies below the heavy Majorana neutrino mass scale M_1, the heavy Majorana neutrino fields are integrated out $\Longrightarrow$ Majorana mass term for the LH flavour neutrinos at $E \sim M_Z$:

$$m_\nu = v^2 \lambda^T\,M^{-1}\,\lambda = U^*\,Diag(m_1, m_2, m_3)\,U^\dagger$$

Type I See-Saw Scenario and Leptogenesis

- Light LH Majorana ν masses introduce a new physical scale: $M \sim 10^{14}\,\mathrm{GeV}$.
- RH heavy Majorana neutrinos N_j, $j = 1, 2, 3$, are produced in thermal scattering after inflation (thermal leptogenesis). Hierarchical spectrum of heavy Majorana neutrinos is assumed: $M_1 \ll M_{2,3}$.
- A lepton asymmetry is dynamically generated through the out of equilibrium decay of the lightest RH Majorana neutrino, N_1, and then converted into a baryon asymmetry, Y_B, due to $(B + L)-$violating sphaleron interactions which exist within the SM.
- Lepton flavour contribution to the generation of the asymmetry can be significant.

Orthogonal Parametrization of λ

- Charged lepton Yukawa interactions enter equilibrium for $T \sim M_1 \lesssim 10^{12}\,\mathrm{GeV} \Longrightarrow$ flavoured leptogenesis.
- Orthogonal parametrization: $RR^T = R^T R = \mathbf{1}$:

  J.A. Casas, A. Ibarra, Nucl. Phys. B 618 (2001) 171

$$\lambda = \frac{1}{v}\sqrt{M}\,R\,\sqrt{m}\,U^\dagger \qquad v = 174\,\mathrm{GeV}$$

  Flavour basis in which the charged lepton Yukawa matrix and the RH neutrino Majorana mass matrix are diagonal.
- At low energy, $E \sim M_Z$, $U \equiv U_{\mathrm{PMNS}}$.
- We want to understand the source of CP-violation generating the CP-asymmetries in the RH neutrino decays:
  - "Low Energy" CP-Violation encoded in U.
  - "High Energy" CP-Violation encoded in R.

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CPV in Flavoured Leptogenesis

- Under CP-invariance, N_j and ν_k have definite CP-parities, $\eta_j^{N\text{CP}} = \pm i$, $\eta_k^{\nu\text{CP}} = \pm i$, and transform in the following way under the CP-symmetry transformation:

$$U_{\text{CP}}\, N_j(x)\, U_{\text{CP}}^\dagger = \eta_j^{N\text{CP}}\, \gamma_0\, N_j(x')\,, \quad \eta_j^{N\text{CP}} = i\rho_j^N = \pm i\,,$$
$$U_{\text{CP}}\, \nu_k(x)\, U_{\text{CP}}^\dagger = \eta_k^{\nu\text{CP}}\, \gamma_0\, \nu_k(x')\,, \quad \eta_k^{\nu\text{CP}} = i\rho_k^\nu = \pm i\,.$$

- CP-invariance of $\mathcal{L}_{\text{Y}}$ ($\eta^{\ell\text{CP}} = i$, $\eta^{H\text{CP}} = 1$):

$$\lambda_{j\ell}^* = \lambda_{j\ell}\,(\eta_j^{N\text{CP}})^*\, \eta^{\ell\text{CP}}\, \eta^{H\text{CP}*}\,, \quad j = 1,2,3,\ \ell = e,\mu,\tau, \tag{1}$$

- If CP-invariance holds at low energy ($E \sim M_Z$):

$$U_{\ell j}^* = U_{\ell j}\, \rho_j^\nu,\,, \quad j = 1,2,3,\ \ell = e,\mu,\tau\,. \tag{2}$$

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CP-Violation in Flavoured Leptogenesis

- (1) and (2) $\Longrightarrow$ R CP-conserving: $R_{jk}{}^* = R_{jk}\, \rho^N_j \rho^\nu_k \; j, k = 1, 2, 3.$
- The violation of CP-symmetry necessary for leptogenesis can be due exclusively to the CP-violating phases in $U_{\rm PMNS}$:

PMNS Neutrino Mixing Matrix

$$U_{\rm PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} {\rm diag}(1, e^{i\frac{\alpha_{21}}{2}}, e^{i\frac{\alpha_{31}}{2}})$$

"low energy" CP-violation in the leptonic sector implies: $\delta \neq \pi q$ (Dirac CPV) or $\alpha_{21} \neq \pi q'$, $\alpha_{31} \neq \pi q''$ (Majorana CPV), $q, q', q'' = 0, 1, 2, \ldots$

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CPV in Flavoured Leptogenesis

CPV in flavoured thermal leptogenesis is triggered by the following quantity:

S. Pascoli, S.T. Petcov, A. Riotto, Nucl. Phys. B 739 (2006) 208

$$P_{jkml} \equiv R_{jk}\, R_{jm}\, U^*_{lk}\, U_{lm}\,,\ \ k \neq m.$$

If CP-invariance holds then P_{jkml} is real:

$$P^*_{jkml} = P_{jkml}\,(\rho^N_j)^2\,(\rho^\nu_k)^2\,(\rho^\nu_m)^2 = P_{jkml}\,,\quad \mathrm{Im}(P_{jkml}) = 0\,.$$

- We consider in detail the case of a real orthogonal matrix R.
- We consider the two possible spectra allowed by data:
  - normal ordering: $m_1 < m_2 < m_3$
  - inverted ordering: $m_3 < m_2 < m_1$
- Analysis performed under the condition of negligible RG running from M_Z to M_1 of m_j and of the parameters in $U_{\mathrm{PMNS}} \Longrightarrow \min(m_j) \lesssim 0.10\mathrm{eV}$.

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Low Energy CP-Violation

For real or purely imaginary $R_{1j}R_{1k}$, $j \neq k$, the CP asymmetries ϵ_ℓ is given by

$$\epsilon_\ell = -\frac{3M_1}{16\pi v^2}\frac{\sum_k \sum_{j>k}\sqrt{m_k m_j}\,(m_j - m_k)\,\rho_{kj}|R_{1k}R_{1j}|\,\mathrm{Im}\,(U^*_{\ell k}U_{\ell j})}{\sum_i m_i\,|R_{1i}|^2},\quad \mathrm{Im}\,(R_{1k}R_{1j}) = 0$$

$$\epsilon_\ell = -\frac{3M_1}{16\pi v^2}\frac{\sum_k \sum_{j>k}\sqrt{m_k m_j}\,(m_j + m_k)\,\rho_{kj}|R_{1k}R_{1j}|\,\mathrm{Re}\,(U^*_{\ell k}U_{\ell j})}{\sum_i m_i\,|R_{1i}|^2},\quad \mathrm{Re}\,(R_{1k}R_{1j}) = 0$$

with $R_{1j}R_{1k} = \rho_{jk}\,|R_{1j}R_{1k}|$ and $R_{1j}R_{1k} = i\rho_{jk}\,|R_{1j}R_{1k}|$, $\rho_{jk} = \pm 1$, $j \neq k$.

- Real (purely imaginary) $R_{1k}R_{1j}$ and purely imaginary (real) $U^*_{\ell k}U_{\ell j}$, $j \neq k$, implies violation of CP-invariance by the matrix R.

  e.g. $\delta = 0$, $\alpha_{31} = \pi$ and $\alpha_{21} = 0$ and real R_{1j}, $j = 1, 2, 3$.

- CP-symmetry is broken at low energies if and only if both $\mathrm{Re}(U^*_{\ell k}U_{\ell j}) \neq 0$ and $\mathrm{Im}(U^*_{\ell k}U_{\ell j}) \neq 0$.

G.C. Branco, M.N. Rebelo, Acta Phys.Polnon.B38:3819-3850,2007.

Inverted hierarchical Light ν mass spectrum ($m_3 \ll m_1 \cong m_2 \cong \sqrt{\Delta m^2_{\rm A}}$)

- In one-flavour approximation the lepton asymmetry is strongly suppressed by the factor $\Delta m^2_\odot / \Delta m^2_{\rm A} \cong 0.032$ and leptogenesis can reproduce the observed baryon asymmetry for $M_1 \gtrsim 7 \times 10^{12}\,\mathrm{GeV}$.
- In flavoured leptogenesis, IH light $\nu's$ and real matrix R, the CP asymmetry is suppressed w.r.t. the one in the NH case by a factor $\sim (\Delta m^2_\odot / \Delta m^2_{\rm A})^{3/4}$. The observed baryon asymmetry can be generated in the case of purely imaginary $R_{11} R_{12}$ or in the supersymmetric version of leptogenesis.
- Baryon asymmetry can be reproduced in flavoured leptogenesis and real R if one considers a non negligible lightest neutrino mass m_3.
- If Y_B is produced in the two-flavour regime ($10^9\ \mathrm{GeV} \lesssim M_1 \lesssim 10^{12}\ \mathrm{GeV}$) the terms $\propto \sqrt{m_3}$ in ϵ_ℓ will be dominant if:

$$2 \left(\frac{m_3}{\sqrt{\Delta m^2_\odot}} \right)^{\frac{1}{2}} \left(\frac{\Delta m^2_{\rm A}}{\Delta m^2_\odot} \right)^{\frac{3}{4}} \frac{|R_{13}|}{|R_{11(12)}|} \gg 1\,. \quad (5)$$

$\Longrightarrow$ $R_{11} \to 0$ or $R_{12} \to 0$ and if m_3 is sufficiently large. No suppression due to the factor $\Delta m^2_\odot / \Delta m^2_{\rm A} \cong 0.032$.

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Inverted ordering ($m_3 < m_2 < m_1$) with $10^{-10}\,\mathrm{eV} \leq m_3 \leq 0.05\,\mathrm{eV}$:

- IH mass spectrum ($10^{-6}\mathrm{eV} \lesssim m_3 \lesssim 5 \times 10^{-3}\mathrm{eV}$, $m_3 \ll m_1 < m_2$, $m_{1,2} \cong \sqrt{|\Delta m^2_{\mathrm{A}}|}$) and real elements R_{1j}. The effects are particularly large for $R_{11} \cong 0$ or $R_{12} \cong 0 \implies$ enhancement by a factor ~ 100 with respect to the case $m_3 \cong 0$.

  S. Pascoli, S.T. Petcov, A. Riotto, Nucl. Phys. B 739 (2006) 208

- Baryon asymmetry for CP-violation due to effective Majorana phase $\alpha_{32} \equiv \alpha_{31} - \alpha_{21} \implies M_1 \gtrsim 3.0 \times 10^{10}\,\mathrm{GeV}$.
- Baryon asymmetry for CP-violation due to Dirac phase δ is obtained fo $M_1 \gtrsim 10^{11}\,\mathrm{GeV}$.
- Successful "flavoured" leptogenesis for Dirac CP-violation gives the following bounds: $\sin\theta_{13} \gtrsim (0.04 - 0.09)$, $|J_{\mathrm{CP}}| \equiv |\mathrm{Im}\{U_{e1} U_{\mu 2} U^*_{e2} U^*_{\mu 1}\}| \gtrsim (0.009 - 0.020)$.

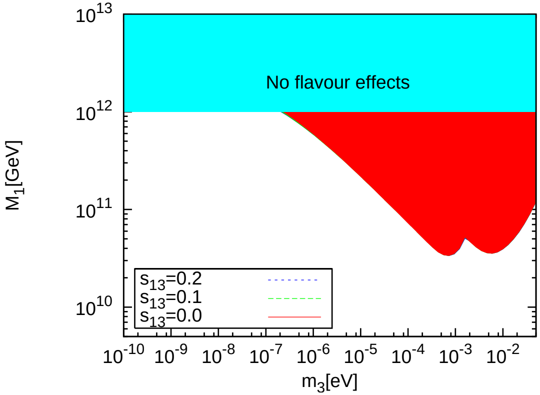

Figure: Values of m_3 and M_1 for which the "flavoured" leptogenesis is successful, generating baryon asymmetry $|Y_B| = 8.6 \times 10^{-11}$ (red/dark shaded area). Light neutrino mass spectrum with inverted ordering (hierarchy), $m_3 < m_1 < m_2$, and real elements R_{1j} of the matrix R. CP-violation due to the Majorana phases in the PMNS matrix. The results shown are obtained using the best fit values of neutrino oscillation parameters: $\Delta m^2_\odot = 8.0 \times 10^{-5}\ \mathrm{eV}^2$, $\Delta m^2_\mathrm{A} = 2.5 \times 10^{-3}\ \mathrm{eV}^2$, $\sin^2\theta_{12} = 0.30$ and $\sin^2 2\theta_{23} = 1$.

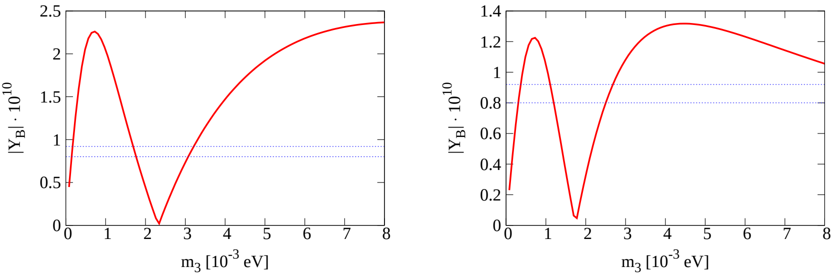

Figure: The dependence of $|Y_B|$ on m_3 in the case of IH spectrum, real $R_{1j}R_{1k}$, Majorana CP-violation, $R_{11} = 0$, $\alpha_{32} = \pi/2$, $s_{13} = 0$, $M_1 = 10^{11}$ GeV, and for i) $\mathrm{sgn}(R_{12}R_{13}) = +1$ (left panel), and ii) $\mathrm{sgn}(R_{12}R_{13}) = -1$ (right panel). The baryon asymmetry $|Y_B|$ is computed for a given m_3, using the value of $|R_{12}|$, for which the CP-asymmetry $|\epsilon_\tau|$ is maximal. The horizontal dotted lines indicate the allowed range of $|Y_B|$, $|Y_B| = (8.0 - 9.2) \times 10^{-11}$.

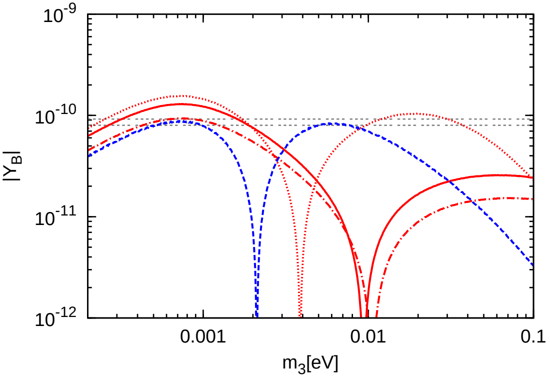

Figure: The dependence of $|Y_B|$ on m_3 in the case of spectrum with inverted ordering (hierarchy), real $R_{1j}R_{1k}$ and Dirac CP-violation, for $R_{11} = 0$, $\delta = \pi/2$, $s_{13} = 0.2$, $\alpha_{32} = 0$, $M_1 = 2.5 \times 10^{11}$ GeV and $\text{sgn}(R_{12}R_{13}) = +1\ (-1)$ (red lines (blue dashed line)). The baryon asymmetry $|Y_B|$ was calculated for a given m_3, using the value of $|R_{12}|$, for which the CP-asymmetry $|\epsilon_\tau|$ is maximal. The results shown for $\text{sgn}(R_{12}R_{13}) = +1$ are obtained for $\sin^2\theta_{23} = 0.50;\ 0.36;\ 0.64$ (red solid, dotted and dash-dotted lines), while those for $\text{sgn}(R_{12}R_{13}) = -1$ correspond to $\sin^2\theta_{23} = 0.5$.

Normal ordering ($m_1 < m_2 < m_3$) with $10^{-10}\,\mathrm{eV} \le m_1 \le 0.05\,\mathrm{eV}$:

- For $m_1 \lesssim 7.5 \times 10^{-3}\,\mathrm{eV}$, Y_B is the same as in the case $m_1 = 0$.
- For $m_1 \gtrsim 10^{-2}\,\mathrm{eV}$, the lightest neutrino mass has a suppressing effect on the asymmetry Y_B.
- If $R_{12} \cong 0$, Y_B has qualitatively the same depedence on the lightest neutrino mass as in the IH spectrum. It is possible to produce the observed baryon asymmetry for CP-violation due to Majorana phases in U_{PMNS} and $M_1 \gtrsim 5.3 \times 10^{10}\,\mathrm{GeV}$.

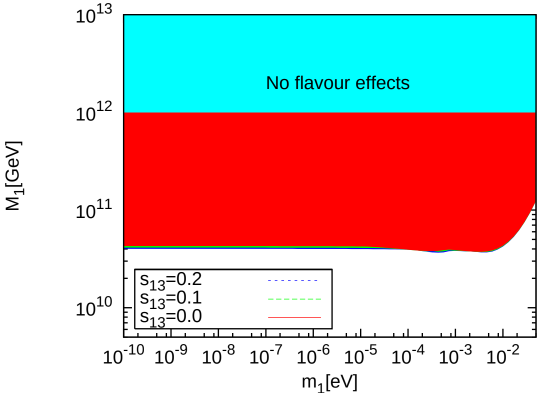

Figure: Values of m_1 and M_1 for which the "flavoured" leptogenesis is successful and baryon asymmetry $Y_B = 8.6 \times 10^{-11}$ can be generated (red shaded area). Light neutrino mass spectrum with normal ordering. The CP-violation necessary for leptogenesis is due to the Majorana and Dirac phases in the PMNS matrix. The results shown are obtained using the best fit values of neutrino oscillation parameters: $\Delta m^2_{\odot} = 8.0 \times 10^{-5}\ \mathrm{eV}^2$, $\Delta m^2_{\mathrm{A}} = 2.5 \times 10^{-3}\ \mathrm{eV}^2$, $\sin^2\theta_{12} = 0.30$ and $\sin^2 2\theta_{23} = 1$.

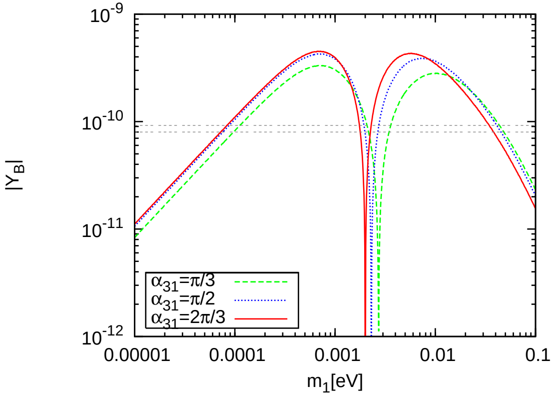

Figure: The dependence of $|Y_B|$ on m_1 in the case of neutrino mass spectrum with normal ordering and real $R_{1j}R_{1k}$, for $R_{12} = 0$, $s_{13} = 0$, $M_1 = 3 \times 10^{11}$ GeV and $\mathrm{sgn}(R_{11}R_{13}) = -1$. The red solid, the blue dotted, and the green dashed lines correspond to $\alpha_{31} = 2\pi/3$, $\pi/2$, and $\pi/3$ respectively. The figure is obtained for $\theta_{23} = \pi/4$.