On the Interplay Between the “Low” and “High” Energy CP-Violation in Leptogenesis

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Outline

1. Matter-Antimatter Asymmetry
    - Leptogenesis Scenario
    - See-Saw Mechanism
2. Flavour Dynamics
    - Neutrino Yukawa Couplings
    - CP Violation
3. Interplay between different sources of CP violation
4. Conclusions

Baryogenesis

The Matter-Antimatter Asymmetry of the Universe can be inferred in two independent ways: via the Big Bang Nucleosynthesis and from the Cosmic Microwave Background. It can be defined as:

$$\eta \equiv \left.\frac{n_B - \bar{n}_B}{n_\gamma}\right|_0 = (6.15 \pm 0.25) \times 10^{-10}$$

$$Y_B \equiv \left.\frac{n_B - \bar{n}_B}{s}\right|_0 = (8.66 \pm 0.35) \times 10^{-11}$$

Y_B must be generated dynamically $\Longrightarrow$ *baryogenesis*.

$$\Downarrow$$

Sakharov's conditions must be satisfied:

A.D. Sakharov, JETP Lett. 5 (1967) 24

- Baryon number violating interactions
- C and CP violation
- Out of equilibrium dynamics

Leptogenesis Scenario

All these ingredients are already present in the Standard Model but we need to extend the theory in order explain *quantitatively* Y_B, at least in two ways: *i*) new sources of CP violation and *ii*) departure from thermal equilibrium in addition to the Electroweak Phase Transition or its modification.

Leptogenesis:

M. Fukugita, T. Yanagida, Phys. Lett. B 174 (1986) 45

out of equilibrium Lepton number violating decays of heavy Majorana neutrinos $\Longrightarrow$ a net lepton asymmetry, Y_L, is produced, converted into a baryon asymmetry Y_B through $(B+L)-$violating anomalous sphaleron interactions:

$$Y_B \approx 10^{-3} \sum_k \epsilon_k \, \eta_k$$

- This scenario could be related to the origin of the neutrino masses $\Longrightarrow$ see-saw mechanism of neutrino mass generation

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, $j = 1, 2, 3$, can be produced in thermal scattering after inflation (Thermal Leptogenesis).

If the spectrum of heavy Majorana neutrinos is strongly hierarchical:

$$M_1 \ll M_{2,3}$$

- 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.
- A lower bound on RH neutrino mass scale and reheating temperature is derived:
  S.Davidson and A. Ibarra, Phys. Lett. B 535 (2002) 25

  W. Buchmller, P. Di Bari, M. Plmacher, Phys. Lett. B 547

$$M_1 \gtrsim 3 \times 10^9\,\mathrm{GeV}$$
$$T_{\mathrm{reh}} \cong (1-10)\,M_1$$

There are two sources of flavour effects: *i*) charged lepton Yukawa couplings $h_{e,\mu,\tau}$ and *ii*) neutrino Yukawa couplings $\lambda_{k\ell}$.

i) Charged lepton Yukawa interactions enter in equilibrium for $T \sim M_1 \lesssim 10^{12}\,\mathrm{GeV} \Longrightarrow$ Flavoured Leptogenesis.

ii) 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.

CP Violation in Flavoured Leptogenesis

- R CP-conserving $\Longrightarrow$ $R_{jk}{}^{*} = \pm R_{jk}\, j,k = 1,2,3.$
- 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) and/or $\alpha_{21} \neq \pi q'$, $\alpha_{31} \neq \pi q''$ (Majorana CPV), $q, q', q'' = 0, 1, 2, \ldots$

CP Violation in Flavoured Leptogenesis

- Under CP-invariance, N_j and ν_k have definite CP-parities, $\eta_j^{N\mathrm{CP}} = \rho_j^N i = \pm i$, $\eta_k^{\nu\mathrm{CP}} = \rho_j^\nu i = \pm i$
- CP Violation in flavoured thermal leptogenesis is triggered by the following quantity:

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

$$P_{jkm\ell} \equiv R_{jk}\, R_{jm}\, U^*_{\ell k}\, U_{\ell m}\,, \;\; k \neq m.$$

- If CP-invariance holds then $P_{jkm\ell}$ is real:

$$P^*_{jkm\ell} = P_{jkm\ell}\,(\rho_j^N)^2\,(\rho_k^\nu)^2\,(\rho_m^\nu)^2 = P_{jkm\ell}\,, \quad \mathrm{Im}(P_{jkm\ell}) = 0\,.$$

Interplay between the 'Low' and 'High' Energy Phases

* E. M., S.T. Petcov, "The Interplay between the 'Low' and 'High' Energy CP-Violation in Thermal Leptogenesis", Eur.Phys.J.C61,93-109,2009

* E. M. and S. T. Petcov, "A Case of Subdominant/Suppressed 'High Energy' Contribution to the Baryon

Asymmetry of the Universe in Flavoured Leptogenesis",Phys. Lett. B **671** (2009) 60

- We work in the context of "flavoured" thermal leptogenesis.
- We consider the general case in which the CP-violation, necessary in order to have successful leptogenesis, is given by the combined effect of "High Energy" and "Low Energy" CP-violating phases.
- We consider the extension of the SM with three heavy RH Majorana neutrinos.
- The particular case of light neutrino mass spectrum with inverted hierarchy is analized in detail.

CP asymmetry for a light ν mass spectrum with inverse hierarchy

The analysis performed is valid in the region of the leptogenesis parameter space corresponding to:

- light ν mass spectrum with inverse hierarchy: $m_3 \ll m_1 \cong m_2 \cong \sqrt{\Delta m^2_{\rm A}}$ (terms proportional to $m_3^2|R_{13}|^2$ negligible),
- $5 \times 10^{10}\mathrm{GeV} \lesssim M_1 \lesssim 10^{12}\mathrm{GeV}$ (two-flavour regime region plus CPV from U),
- $|R_{13}|^2|\sin 2\tilde{\varphi}_{13}| \ll \min(|R_{11}|^2|\sin 2\tilde{\varphi}_{11}|, |R_{12}|^2|\sin 2\tilde{\varphi}_{12}|)$. This condition can be satisfied for $\mathrm{Im}(R_{13}^2) = 0$. The case $R_{13} = 0$ is compatible with the hypothesis of N_3 decoupling.

From the orthogonality condition $R_{11}^2 + R_{12}^2 + R_{13}^2 = 1$, $R_{1j} \equiv |R_{1j}|e^{i\tilde{\varphi}_{1j}}$, $j = 1, 2$ and $\mathrm{Im}(R_{13}^2) = 0$:

$$\cos 2\tilde{\varphi}_{11} = \frac{\left(1 - R_{13}^2\right)^2 + |R_{11}|^4 - |R_{12}|^4}{2|R_{11}|^2\,(1 - R_{13}^2)}$$

$$\cos 2\tilde{\varphi}_{12} = \frac{\left(1 - R_{13}^2\right)^2 - |R_{11}|^4 + |R_{12}|^4}{2|R_{12}|^2\,(1 - R_{13}^2)}$$

CP asymmetry for a light ν mass spectrum with inverse hierarchy

CP asymmetry in the flavour ℓ:

$$\epsilon_\ell = -\frac{3M_1}{16\pi v^2} \frac{\mathrm{Im}\left(\sum_{j,k} m_j^{1/2} m_k^{3/2} U^*_{\ell j} U_{\ell k} R_{1j} R_{1k}\right)}{\sum_\beta m_\beta \, |R_{1\beta}|^2} , \quad \ell = e, \mu, \tau \, .$$

In the two flavour regime and inverted hierarchical light ν mass spectrum:

$$\epsilon_2 \equiv \epsilon_e + \epsilon_\mu \cong -\epsilon_\tau + O(\Delta m^2_\odot / |\Delta m^2_\mathrm{A}|) \epsilon_{max}$$

Different contributions to Y_B

$$
\begin{aligned}
Y_B &= -\frac{12}{37}\frac{\epsilon_\tau}{g_*}\left(\eta\left(\frac{390}{589}\widetilde{m}_\tau\right) - \eta\left(\frac{417}{589}\widetilde{m}_2\right)\right) \\
&\equiv Y_B^0(A_{\rm HE} + A_{\rm MIX})
\end{aligned}
$$

where $A_{\rm HE(MIX)} \equiv C_{\rm HE(MIX)}(\eta(0.66\widetilde{m}_\tau) - \eta(0.71\widetilde{m}_2))$ and

$$
Y_B^0 \cong 3 \times 10^{-10}\left(\frac{M_1}{10^9\ {\rm GeV}}\right)\left(\frac{\sqrt{\Delta m^2_{\rm A}}}{5 \times 10^{-2}\ {\rm eV}}\right)
$$

$$
C_{\rm HE} = G_{11}\ \sin 2\tilde{\varphi}_{11}\left[\,|U_{\tau 1}|^2 - |U_{\tau 2}|^2\,\right],
$$

$$
C_{\rm MIX} \cong 2\,G_{12}\ \sin(\tilde{\varphi}_{11} + \tilde{\varphi}_{12})\,{\rm Re}(U^*_{\tau 1}U_{\tau 2}),
$$

where $G_{11} \equiv |R_{11}|^2/(|R_{11}|^2 + |R_{12}|^2)$, $G_{12} \equiv |R_{11}R_{12}|/(|R_{11}|^2 + |R_{12}|^2)$

Non trivial effects of a sufficiently large θ_{13}

The purely high energy term, $Y_B^0 A_{\rm HE}$, can be hugely suppressed by the factor:

$$\begin{aligned} |U_{\tau 1}|^2 - |U_{\tau 2}|^2 &\cong (s_{12}^2 - c_{12}^2) s_{23}^2 - 4 s_{12} c_{12} s_{23} c_{23} s_{13} \cos\delta \\ &\cong -0.20 - 0.92\, s_{13}\, \cos\delta \end{aligned}$$

with $s_{12}^2 = 0.30$ and $s_{23}^2 = 0.5$. In particular:

- for $(-\sin\theta_{13}\cos\delta) > 0.17$ and $M_1 \lesssim 5 \times 10^{11}{\rm GeV}$ Y_B cannot be generated by the "high energy" term $Y_B^0 A_{\rm HE}$;
- the suppression remains in all the range of variability of $|R_{12}|$: $|(1-|R_{11}|^2)| \lesssim |R_{12}|^2 \lesssim (1+|R_{11}|^2)$ and for $0.3 \lesssim |R_{11}| \lesssim 1.2$;
- for $s_{12}^2 = 0.38$ and $s_{23}^2 = 0.36$, the same conclusion is valid if $0.06 \lesssim (-\sin\theta_{13}\cos\delta) \lesssim 0.12$;
- such values of $\sin\theta_{13}$ and $\sin\theta_{13}\cos\delta$ can be probed in the Double CHOOZ and Daya Bay reactor neutrino experiments and by the planned accelerator experiments on CP violation in neutrino oscillations.

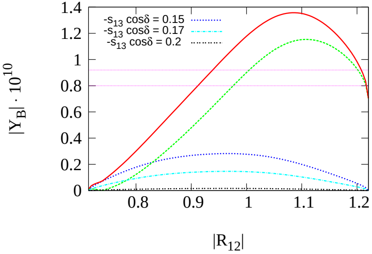


Figure: The dependence of the "high energy" term $|Y_B^0 A_{\rm HE}|$ (blue line), the "mixed" term $|Y_B^0 A_{\rm MIX}|$ (green line) and of the total baryon asymmetry $|Y_B|$ (red line) on $|R_{12}|$ in the case of IH spectrum, CP-violation due to the Majorana phase α_{21} and R-phases, for $(-s_{13}\cos\delta) = 0.15;\ 0.17;\ 0.20$, $\alpha_{21} = \pi/2$, $|R_{11}| = 0.7$, $M_1 = 10^{11}$ GeV. The horizontal lines indicate the allowed range of $|Y_B|$, $|Y_B| = (8.0 - 9.2) \times 10^{-11}$.

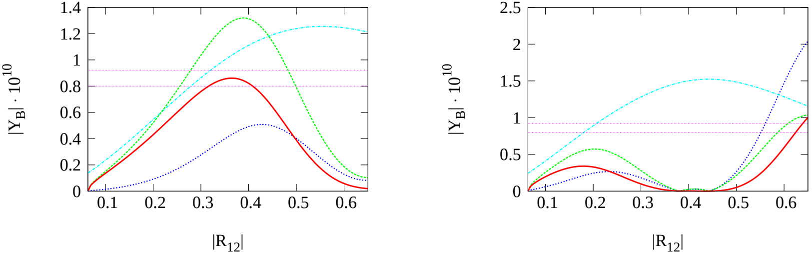
A $\sim 2\sigma$ indication of a non zero value of $\sin^2\theta_{13}$ was reported in:
* G. L. Fogli et al., arXiv:0905.3549.
* G. L. Fogli et al., Phys.Rev.Lett. **101** (2008). See also:
* J. Escamilla, D. C. Latimer and D. J. Ernst, arXiv:0805.2924.
$\sin^2\theta_{13} = 0.02 \pm 0.01$ $[1\sigma]$. Moreover, $\cos\delta = -1$ is reported to be preferred over $\cos\delta = +1$ by atmospheric neutrino data ($-\cos\delta\sin\theta_{13} > 0$).

Effect of the Majorana CP violating phase α_{21} on Y_B

- Subdominant contribution of the “high energy” term takes place also in the case of $\sin\theta_{13} = 0$.
- e.g. : $|R_{11}| \cong 1$ and $R_{13} = 0$ (decoupling of N_3) impliy:

$$|A_{\mathrm{HE}}| \propto |G_{11} \sin 2\tilde{\varphi}_{11}| \propto |R_{11} R_{12}|^2$$
$$|A_{\mathrm{MIX}}| \propto 2|G_{12} \sin(\tilde{\varphi}_{11} + \tilde{\varphi}_{12})| \propto \sqrt{2}|R_{11} R_{12}|$$

  For $|R_{12}| \gtrsim 0.8$ and $M_1 \gtrsim 7 \times 10^{10}\mathrm{GeV}$, the “high energy” term in $|Y_B|$ is the dominant one and can provide the requisite baryon asymmetry compatible with the observations.
- In the more general case in which $R_{13} \neq 0$ and $\mathrm{Im}(R_{13}^2) = 0$, the mixed term gives the dominant contribution roughly in half of the parameter space provided $0 \leq |R_{13}| \lesssim 0.9$,$1.05 \lesssim |R_{12}| \lesssim 1.5$, and $0.3 \lesssim |R_{11}| \lesssim 1.2$. Washout effects do not cancel the baryon asymmetry for $0 < \alpha_{21} \lesssim 2\pi/3$. Successful leptogenesis can be realized in the two flavoured regime if the RH Majorana neutrino mass lies in the interval 5×10^{10} GeV $\lesssim M_1 \lesssim 7 \times 10^{11}$ GeV.



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Conclusions

The results obtained in this study show that in the "flavoured" leptogenesis scenario, the contribution to Y_B due to the "low energy" CP-violating Majorana and Dirac phases in the neutrino mixing matrix, *in certain physically interesting cases*, like
i) IH light neutrino mass spectrum,
ii) relatively large value of $(-\sin\theta_{13}\cos\delta)$, etc.,
can play an important role in the generation of the observed baryon asymmetry of the Universe even in the presence of "high energy" CP-violation, generated by additional physical phases in the matrix of neutrino Yukawa couplings.