Mixed Seesaw Mechanism and consequences for Leptogenesis

Pierre Hosteins
En collaboration avec Stéphane Lavignac et Carlos Savoy

Service de Physique Théorique, CEA-Saclay

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Laboratoire de l'Accélérateur Linéaire
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- Consequences for leptogenesis and lepton flavor violation
- Conclusions and perspectives

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- **Type I seesaw** : addition of 3 right-handed neutrinos N_{Ri} with the couplings :

$$Y_\nu \overline{N}_R l_L H + \frac{1}{2} M_R \overline{N}_R N_R^c + \text{h.c.}$$

which provides a mass matrix for the light neutrinos :

$$\mathbf{m}_\nu = -\mathbf{v}^2 \mathbf{Y}_\nu^\mathbf{T} \mathbf{M}_\mathbf{R}^{-1} \mathbf{Y}_\nu \ll v$$

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- **Type II seesaw** : addition of a scalar triplet of $SU(2)_L$ Δ_L :

$$\frac{1}{2} f_L \overline{l}_L^c \Delta_L l_L \qquad \Rightarrow \qquad \mathbf{m}_\nu = \mathbf{v}_\mathbf{L} \mathbf{f}_\mathbf{L}$$

which requires : $v_L \sim m_\nu$ and a triplet heavy enough.

In some Grand Unified theories both these triplet and singlet particules under $SU(2)_L$ are present and m_ν is given by :

$$m_\nu = v_L f_L - v^2 Y_\nu^T M_R^{-1} Y_\nu$$

Usually the majorana mass M_R of the N_R comes from the vev of an $SU(2)_R$ triplet Δ_R of the order of the breaking of the B-L quantum number breaking scale.

In these setups, very often there is a symmetry between the $SU(2)_L$ and $SU(2)_R$ gauge groups (Left-Right symmetric theories) giving :
$f_L = f_R = f$

$$\mathbf{m}_\nu = \mathbf{v_L f} - \frac{\mathbf{v^2}}{\mathbf{v_R}} \mathbf{Y}_\nu^{\mathbf{T}} \mathbf{f}^{-1} \mathbf{Y}_\nu \qquad \text{with f symmetric}$$

This is the general formula we are going to stick to.

SO(10) Grand Unification

The principle of Grand Unification :

Within supersymmetry, the gauge coupling constants meet around $E \sim 2.10^{16}$GeV. This can be explained by gauge unification :

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Moreover GUTs explain the accidental cancellation of anomalies, the quantisation of electric charge...

SO(10) setup

The theory being supersymmetric, every fermion has a bosonic partner and vice-versa, unified inside a “superfield”.
Moreover, RH particles are unified inside doublets of $SU(2)_R$ (for example : $l_R = (N_R e_R)^T$) $\Rightarrow$ majorana mass for N_R.

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Interactions are coded in the superpotential W, here we choose a particle content such that the Yukawa part is :

$$W \supset Y_{uij} 16_i 16_j 10_u + Y_{dij} 16_i 16_j 10_d + f_{ij} 16_i 16_j \overline{126}$$

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with : $\langle \Delta_R^0 \rangle = v_R \sim 10^{12}$–$10^{17}$ GeV, $\langle \Delta_L^0 \rangle = v_L \sim \frac{v^2}{v_R}$

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and $SO(10)$ gives the interesting relations : $Y_\nu = Y_u$ and $Y_e = Y_d$

The method of reconstruction

We have only symmetric matrices.

After the breaking of $SU(2)_L$ and $SU(2)_R$, the mass matrix is :

$$m_\nu = \alpha f - \beta Y_\nu \frac{1}{f} Y_\nu \qquad \text{with :} \quad \alpha = v_L \qquad \beta = \frac{v^2}{v_R}$$

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$$Z = Y_\nu^{-\frac{1}{2}} m_\nu (Y_\nu^{-\frac{1}{2}})^T \qquad X = Y_\nu^{-\frac{1}{2}} f (Y_\nu^{-\frac{1}{2}})^T$$

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with Z known and symmetric $\Rightarrow$ diagonalisable by a **complex orthogonal transformation** O_Z, and $O_Z = O_X$.

$$x_i^\pm = \frac{z_i \pm \sqrt{z_i^2 + 4\alpha\beta}}{2}$$

$\Rightarrow$ **8 solutions for f** (Akhmedov-Frigerio) labeled by "$+++$","$++-$", etc...

We can then reconstruct the N_R mass matrix $M_R = v_R f = U_R D_R U_R^T$.

From the solutions we find, we can identify some known cases :
when $\alpha\beta$ is small enough we have for the $(+++)$ and $(---)$ solutions

$$f^{(+++)} \longrightarrow \frac{M_\nu}{v_L} \qquad \text{(type II limit)}$$

$$f^{(---)} \longrightarrow -\frac{v^2}{v_R} Y_\nu M_\nu^{-1} Y_\nu \qquad \text{(type I limit)}$$

These limits will allow us to compare our results with previous studies taking into account only type I or type II seesaw.

Mass Spectra

In order to calculate f we have to know the low energy neutrino parameters : we choose the values of Foli and coll. fit (hep-ph/0506307) and we fix $m_1 = 10^{-3}$eV (normal hierarchy).
We checked that changing the hirerarchy does not change the qualitative results.

Free parameters : $\mathbf{v_R}$, $\frac{\beta}{\alpha} = \frac{\mathbf{v}^2}{\mathbf{v_L v_R}}$ **and 13 complex phases**

We allow v_R to vary in the range $[10^{12} GeV, 10^{17} GeV]$.

When diagonalising $M_R = v_R f$, we will try to avoid too large a cancellation between the two contributions to m_ν.

Mass Spectra

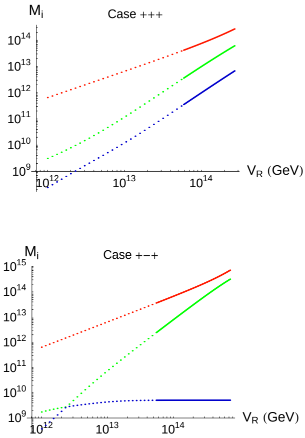

Figure: 4 different mass spectra of heavy neutrinos as function of v_R (dotted region is fine-tuned)

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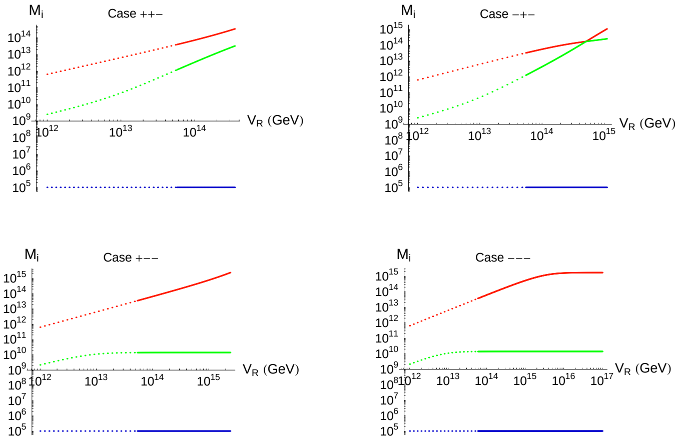

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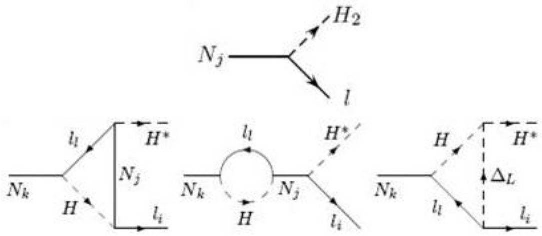
Leptogenesis

The couplings of N_{Ri} and Δ_L being complex, they violate the CP symmetry $\Rightarrow$ the heavy neutrinos N_i do not decay symmetrycally into leptons and anti-leptons.

Supposing that N_i are produced in the early universe (either by decay of the inflaton or thermally) they begin to decay at $T \sim M_i$ and create an asymmetry :

$$\varepsilon_{\rm CP} = \frac{\Gamma(N_i \to lH) - \Gamma(N_i \to \bar{l}\bar{H})}{\Gamma(N_i \to lH) + \Gamma(N_i \to \bar{l}\bar{H})}$$



Leptogenesis

When the spectrum is hierarchical the loop contributions give :

$$\varepsilon_{\text{CP}} \simeq \frac{3}{8\pi} \frac{\text{Im}[Y m_\nu^* Y^T]_{11}}{(YY^\dagger)_{11}} \frac{M_1}{v^2}$$

The baryon asymmetry is then given by :

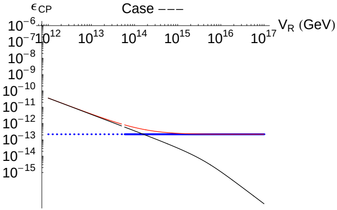
$$\frac{n_B}{n_S} \sim 10^{-3} \kappa\, \varepsilon_{\text{CP}} \sim 10^{-10} \quad \Longrightarrow \quad \varepsilon_{\text{CP}} \gtrsim 10^{-6}$$

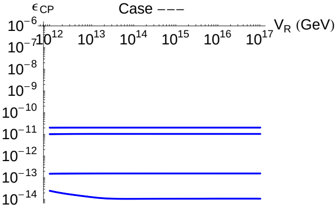
where κ is a wash-out factor due to inverse decay $\Rightarrow$ we did not study the wash-out.

We find 3 types of situations for leptogenesis :

Leptogenesis

Cases with $M_1 \sim 10^5\text{GeV}$:

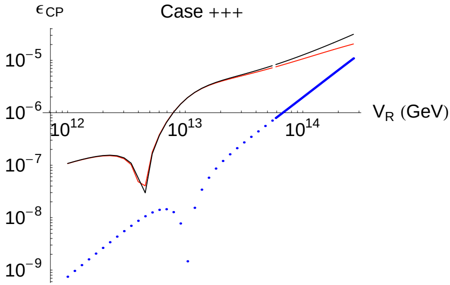




By the same reason why type I doesn't work in SO(10) (M_1 too small) leptogenesis doesn't work for these 4 cases, even including recently studied flavour effects (Vives).

Leptogenesis

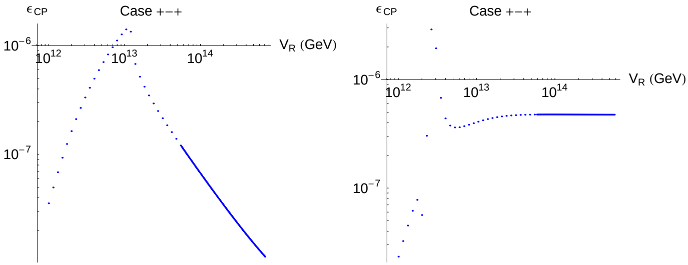
Cases with M_1 heavy ($\gtrsim 10^10$GeV) :



Leptogenesis easily accomodated, but often in the fine-tuned region.

Leptogenesis

Cases with $M_1 \sim \text{few}10^9\text{GeV}$:



Cases allowed for some specific choices of the phases.

Lepton Flavor Violation

The superpartners of the leptons ("sleptons") can induce lepton flavor violating processes.

If the SUSY breaking terms are flavor blind, like in mSUGRA, some amount of flavour violation can be created through the running from M_{Planck}, due to Δ_L and N_{Ri}.

The relation for the branching ratios :

$$\frac{BR(l_j \to l_i \gamma)}{BR(l_j \to l_i \bar{\nu}_i \nu_j)} \propto |(m^2_{\tilde{L}})_{ij}|^2 \propto |C_{ij}|^2$$

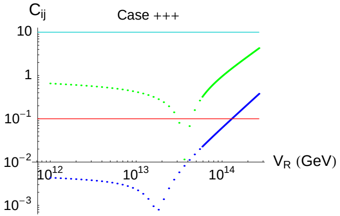
means we can parametrise the constraints from $\mu \to e\gamma$ and $\tau \to \mu\gamma$ by the quantities :

$$C_{ij} = (Y^\dagger \ln(M_U/M_R) Y)_{ij} + 2(f^\dagger \ln(M_U/M_\Delta) f)_{ij}$$

Lepton Flavor Violation

$$BR(\mu \rightarrow e\gamma) < 1.2 \times 10^{-11} \quad \Rightarrow \quad |\mathbf{C}_{\mathbf{e}\mu}| < \mathbf{0.1}$$

$$BR(\tau \rightarrow \mu\gamma) < 6.8 \times 10^{-8} \quad \Rightarrow \quad |\mathbf{C}_{\mu\tau}| < \mathbf{10}$$



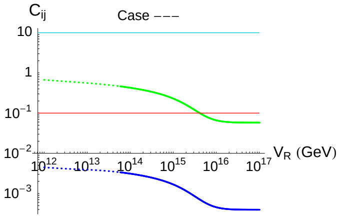


Figure: $\mu \rightarrow e\gamma$ (blue curve) and $\tau \rightarrow \mu\gamma$ (green curve) with present experimental limits (red and light blue)

However, the limits drawn are dependent of the supersymmetric parameters (masses of the superpartners, tan β...)

E_6 Unification ?

If we want to accomodate the baryon asymmetry of the Universe with leptogenesis, we saw that 4 of the 8 solutions are clearly excluded.

From those which remain, some of them give a correct CP asymmetry in the fine-tuned region. These solutions would seem unnatural if this alignment $Y_\nu \propto f$ is not motivated by an underlying symmetry :

$\Rightarrow$ We can link these two couplings by embedding $SO(10)$ into $\mathbf{E_6}$

$$(10_u, 54, \overline{126}) \subset 351'$$

But there has to be no other contribution to the mass of Δ_L.

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- We only studied a toy model and should check if we can solve for a more realistic model : however we expect that it will give qualitatively comparable results

Perspectives

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  There will be states with intermediate masses $\Rightarrow$ potentially mediate dangerous proton decay or spoil the gauge couplings unification.

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  There will be states with intermediate masses $\Rightarrow$ potentially mediate dangerous proton decay or spoil the gauge couplings unification.

- The reconstruction procedure can only be applied with **symmetric matrices** in m_ν, i.e. we cannot say anything if a 120 dimensional representation contributes to the neutrino masses.