

Leptogenesis and
neutrino physics

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1 – Outline

- Low energy neutrino parameters
- The see-saw mechanism
- Leptogenesis
- On the connection between CPV phases in leptogenesis and m_ν
- Questions for the future

2 – Neutrino parameters at low energy

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To explain the present data we need to assume (at least) **3 generations**.

We have 3 masses: $m_1, \quad m_2 = \sqrt{m_1^2 + \Delta m_{21}^2}, \quad m_3 = \sqrt{m_1^2 + \Delta m_{31}^2}$

The mixing is described by a unitary mixing matrix:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}e^{i\delta} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$$

parametrized by **3 angles** and **3 phases**.

2 – Neutrino parameters at low energy

In the neutrino mass matrix $m_\nu = U_{PMNS}^T \mathcal{D}_m U_{PMNS}$ we need to measure

• 3 mixing angles: $\theta_A \sim 45^\circ, \theta_\odot \sim 30^\circ, \theta < 12^\circ$.

• 3 masses:

$$m_1$$

$$m_2 = \sqrt{m_1^2 + \Delta m_{21}^2}$$

$$m_3 = \sqrt{m_1^2 + \Delta m_{31}^2};$$

$$\Delta m_{\odot}^2 \sim 8 \times 10^{-5} \text{ eV}^2,$$

$$\Delta m_{\text{atm}}^2 \sim 2 \times 10^{-3} \text{ eV}^2,$$

$$m_1, \text{ sign}(\Delta m_{31}^2).$$

• 3 phases:

universal phase δ

2 Majorana CPV phases, $\alpha_{21,31}$

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Neutrino oscillation experiments

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Direct ν -mass
searches

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$(\beta\beta)_{0\nu}$ -decay

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graph TD; A["(beta beta)_{0 nu}-decay"] --> B["m_1, sign(Delta m_{31}^2)"]; A --> C["universal phase delta"]; A --> D["2 Majorana CPV phases, alpha_{21,31}"];
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NATURE_{of} NEUTRINOS

DIRAC

particles

MAJORANA

particles, $\Delta L = 2$

A Majorana neutrino coincides with its antineutrino. Then the lepton symmetry is not a good symmetry of the theory of Elementary Particles.

The nature of neutrinos is directly related to the fundamental symmetries of elementary particle interactions and is crucial in understanding the theory beyond the SM (e.g. see saw mechanism).

Neutrino oscillation experiments cannot tell anything about the absolute mass scale and the nature of neutrinos. $\Delta L = 2$ processes can answer this question and the most sensitive one is $(\beta\beta)_{0\nu}$ -decay.

3 – See-saw mechanism and leptogenesis

The see-saw mechanism

We assume the existence of very heavy **right-handed neutrinos**, singlet with respect to SM. They have a large **Majorana mass**, $M_R \gg 100 \text{ GeV}$. They couple to the left-handed neutrinos and to the Higgs:

$$Y_L \cdot H N \rightarrow Y \langle H^0 \rangle \nu N = m_D \nu N$$

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

The light-neutrino mass matrix is given by

$$m_\nu \simeq -m_D^T M_R^{-1} m_D \sim \frac{m_D^2}{M_R} \sim \frac{1 \text{ GeV}^2}{10^9 \text{ GeV}} \sim 1 \text{ eV}$$

- The massive neutrinos are **Majorana**.
- It naturally explains the smallness of neutrino masses.
- Leptogenesis takes place in the same context.

3 – See-saw mechanism and leptogenesis

Leptogenesis

A viable explanation for the baryon asymmetry of the Universe

$$\eta_B = 6.5 \times 10^{-10}$$

is the **leptogenesis** mechanism [Fukugita, Yanagida, 1986]. It requires L violation and **CPV**.

The out-of-equilibrium decays of heavy N_R of see-saw models generate a **lepton asymmetry**. This is then converted into the observed **baryon asymmetry**.

$$\begin{aligned} \eta_B &= \alpha k \epsilon_i \\ &\propto k \frac{\sum_{i \neq j} \text{Im}(m_D m_D^\dagger)_{ij}^2}{(m_D m_D^\dagger)_{11}} \left(f\left(\frac{M_j^2}{M_1^2}\right) + g\left(\frac{M_j^2}{M_1^2}\right) \right) \end{aligned}$$

k is an **efficiency factor**, which takes into account the wash-out effects, controlled by

$$\tilde{m}_1 = (m_D m_D^\dagger)_{11} = m_1 |R_{11}^2| + m_2 |R_{12}^2| + m_3 |R_{13}^2|.$$

This allows to put a bound on the range of values of neutrino masses compatible with minimal leptogenesis [Buchmuller, Di Bari, Plumacher]:

$$m_1 < 0.1 - 0.15 \text{ eV} .$$

3 – See-saw mechanism and leptogenesis

Is there any link between CPV in m_ν and the lepton asymmetry?

M_R	3	0	$m_{1,2,3}$	3	0
m_D	9	6	U	3	3
	12	6		6	3

In going from high energy to low energy, 6 real parameters and 3 phases are lost.

Using useful parametrizations we can trace which are the parameters which do not play any role at low energy [Ellis et al.; Ibarra et al.; Branco et al.; Tanimoto et al.; S.P., Petcov, Yaguna, PLB2003; S.P., Petcov, Rodejohann, PRD2003].

- Biunitary parametrization [e.g., Davidson, Ibarra; Ellis et al.; S.P., Petcov, Rodejohann, PRD2003].

$$m_D = U_R^\dagger \mathcal{D}_{md} U_L$$

- Orthogonal parameterization [e.g., S.P., Petcov, Yaguna, PLB2003].

$$d_m^{1/2} d_m^{1/2} = -U^T m_D^T D_M^{-1/2} R R^T D_M^{-1/2} m_D U$$

$$m_D = i D_M^{1/2} R d_m^{1/2} U^\dagger$$

Leptogenesis depends on the mixing in the **right-handed sector**.

m_ν depends on both the mixing matrices for the **left-handed and right-handed sector**.

Leptogenesis

$$\begin{aligned} m_D m_D^\dagger &= U_R^\dagger D_{md}^2 U_R \\ &= D_M^{1/2} R d_m R^\dagger D_M^{1/2} \end{aligned}$$

Neutrino mass matrix

$$\begin{aligned} m_\nu &\simeq -U_L^T m_D U_R^* D_M^{-1} U_R^\dagger m_D U_L \\ &= U^* d_m U^\dagger \end{aligned}$$

- U does not enter explicitly in $m_D m_D^\dagger$.
- $U(\alpha_R, \alpha_L)$

$$U(\alpha_R, \alpha_L)$$

implies that

- there is no one-to-one connection between CPV phases in m_ν and leptogenesis;
- If in a model the number of high energy phases is reduced, then it may be **possible to link** the low-energy parameters with the leptogenesis ones. (For example, models in which $\alpha_L = 0$ or $\alpha_L(\alpha_R)$).

For each model which reproduces the low energy neutrino mass matrix, the **viability of leptogenesis** need to be studied. Typically successful leptogenesis puts **bounds** on the **neutrino parameters** at high and low energy (light and heavy mass scales, CPV phases), [e.g., S.P., Petcov, Yaguna; S.P., Petcov, Rodejohann; Dermisek, Pascoli in prep.].

4 – Conclusions

- Neutrino masses (and their smallness) and mixing require new physics beyond the SM.
 - If neutrinos are Majorana particles, the see-saw mechanism would be a reasonable explanation for neutrino mass generation.
 - Furthermore it would indicate that L is violated and this is one of the necessary ingredients for leptogenesis.
 - Present and future knowledge of m_ν (angles, phases and masses) will allow to test the ν -mass generation models and disprove a large number of them.
- Successful leptogenesis will further restrict the allowed ones and the range of their parameters.

Neutrino physics can shed some light on the physics at very **high energy scales** (and possibly on the **evolution of our Universe**).