Leptogenesis and low-energy CP-violation

BENE & ECFA Muon Study Week

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Silvia Pascoli

CERN

1 – Outline

- Determining the CPV phases in future experiments (long base-line and neutrinoless double beta decay experiments)

- The see-saw mechanism and leptogenesis

- Possible connection between Low energy and High energy (leptogenesis) CP-violation

- Two examples of ”reduced” models.

2 – Dirac and Majorana CPV phases

In the case of 3 neutrino mixing, the unitary lepton mixing matrix can be parametrized as

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

- one universal CPV phase: $\boxed{\delta}$.

It enters both $\Delta L = 0$ and $\Delta L = 2$ processes.

- two Majorana CPV phases $\boxed{\alpha_{21}}$ and $\boxed{\alpha_{31}}$. They are physical only if neutrinos are Majorana particles.

If CP is conserved we have $\alpha_{21}, \alpha_{31} = 0$ (equal CP-parities) or $\alpha_{21}, \alpha_{31} = \pm\pi$ (opposite CP-parities).

3 – Measuring CP-V phases

The δ phase

The Dirac phase δ can be measured in ν-oscillation experiments.

A measure of CP- violating effects is provided by the CP asymmetry:

$$\boxed{A_{CP} = P(\nu_l \to \nu_{l'}) - P(\bar{\nu}_l \to \bar{\nu}_{l'})}$$

In vacuum one has:

$$\boxed{A_{CP}(e,\mu) = J_{CP}\left(\sin\left(\frac{\Delta m^2_{12}}{2E}L\right) + \sin\left(\frac{\Delta m^2_{32}}{2E}L\right) + \sin\left(\frac{\Delta m^2_{13}}{2E}L\right)\right)}$$

$$J_{CP} = c_{13}\sin 2\theta_{13}\ \sin 2\theta_{23}\sin 2\theta_{12}\sin\delta$$

CP-violating effects in neutrino oscillations are suppressed

- for $\sin\theta_{13}$ very small;
- if one mass squared difference can be neglected.

The CP-asymmetry will be searched for in future long base-line experiments, looking for $\nu_\mu \longrightarrow \nu_e (\bar{\nu}_\mu \longrightarrow \bar{\nu}_e)$.

These oscillations take place in matter (Earth). The Earth matter is not charge-symmetric as it is given only by e^-, p and n. Matter effects in oscillations are not CP- neither CPT- invariant.

$$\boxed{\begin{aligned} P(\bar{P}) \simeq \quad & s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{A \mp \Delta_{13}}\right)^2 \sin^2 \frac{(A \mp \Delta_{13})L}{2} \\ & + \tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{A \mp \Delta_{13}} \sin \frac{AL}{2} \sin \frac{(A \mp \Delta_{13})L}{2} \cos \left(\mp \delta + \frac{\Delta_{13} L}{2} \right) \\ & + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2 \frac{AL}{2} \end{aligned}}$$

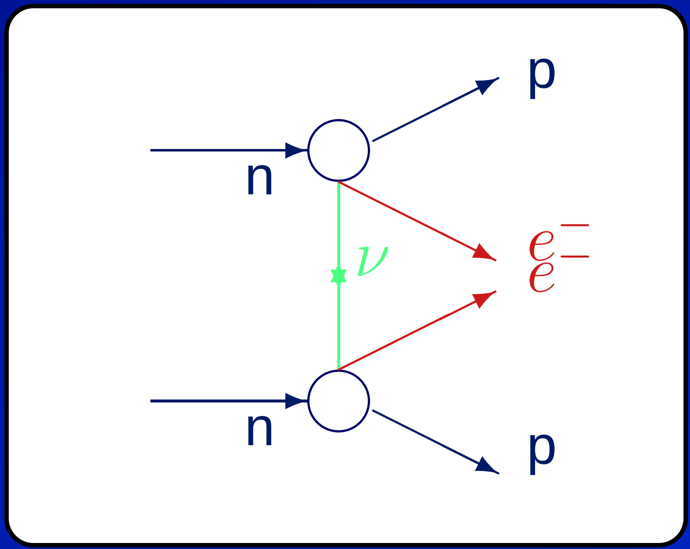
with $\tilde{J} \equiv c_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12}$ and $\Delta_{13} \equiv \Delta m_{31}^2/(2E)$.

It is necessary to disentangle true CP-V effects due to the δ phase from the ones induced by matter and resolve the degeneracies among different parameters. (See T. Schwetz talk)

Majorana phases

Majorana phases can be measured only in processes which violate the lepton number by 2 units ($\Delta L = 2$).

By far, the most sensitive of these processes is neutrinoless double beta decay: $(A, Z) \to (A, Z+2) + 2e^-$.



$(\beta\beta)_{0\nu}$-decay has a special role in the study of neutrino properties, as it probes the violation of **global lepton number**, and it might provide information on the **neutrino mass spectrum, absolute neutrino mass scale and CP-V**.

The half-life time, $T^{1/2}_{0\nu}$, of the $(\beta\beta)_{0\nu}$-decay can be factorized as:

$$\boxed{\left[T^{1/2}_{0\nu}(0^+ \rightarrow 0^+)\right]^{-1} \propto |M_F - g_A^2 M_{GT}|^2 \, |<m>|^{\,2}}$$

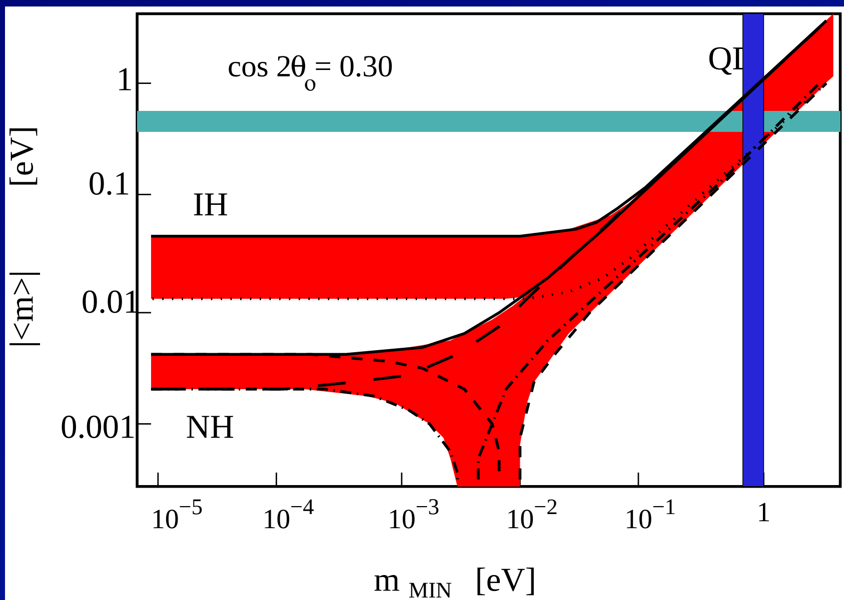
- M_F, M_{GT} are nuclear matrix elements.
- $|<m>|$ **is the effective Majorana mass parameter**:

$$\boxed{|<m>| \; \equiv |\, m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i\alpha_{21}} + m_3|U_{e3}|^2 e^{i\alpha_{31}} \,| \,,}$$

For ex., for quasi degenerate masses, $m_1 \simeq m_2 \simeq m_3$,

$$\boxed{|<m>| \; \simeq m_{\bar{\nu}_e}\left|\left(\cos^2\theta_\odot + \sin^2\theta_\odot e^{i\alpha_{21}}\right)\cos^2\theta_{13} + \sin^2\theta_{13} e^{i\alpha_{31}}\right|}$$

As $|<m>| \; \gtrsim 0.05 \;\; \mathrm{eV}$, all the allowed range for $|<m>|$ is in the range of sensitivity of present and upcoming $(\beta\beta)_{0\nu}$-decay experiments.



In principle, a measurement of $|<m>|$

combined with a measurement of m_1

(in tritium β-decay exp. and/or cosmology)

would allow to establish if

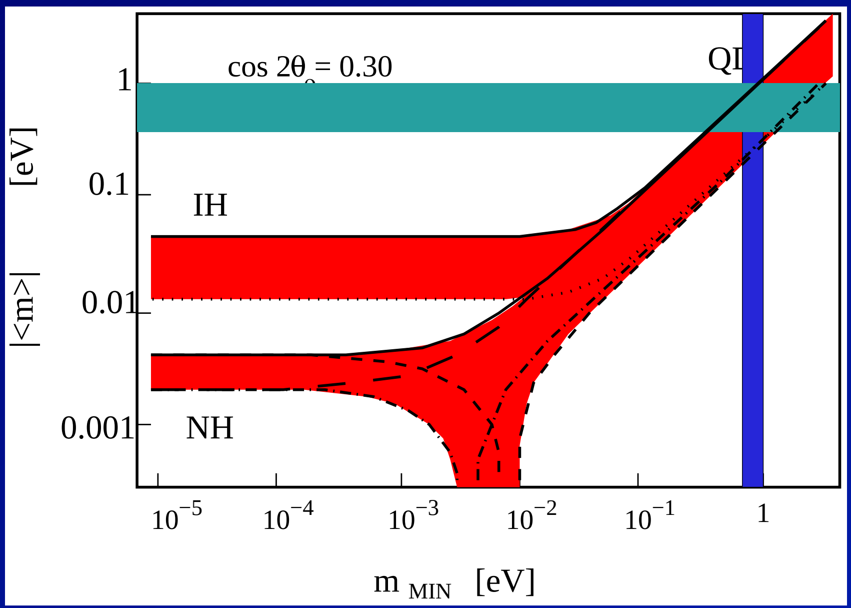
CP is violated

and to constrain the CPV phases,

once the neutrino mass spectrum is known.

For ex., for the QD spectrum, we have:

$$\boxed{\sin^2 \alpha_{21}/2 \simeq \left(1 - \frac{|<m>|^2}{m_{\bar{\nu}_e}{}^2}\right) \frac{1}{\sin^2 2\theta_\odot}.}$$



Due to the experimental errors on the parameters and nuclear matrix elements uncertainties, determining that CP is violated in the lepton sector due to Majorana CPV phases is challenging.

(Barger et al.; S.P., Petcov, Rodejohann)

Establishing CPV due to Majorana CPV phases requires: (S.P., Petcov, Rodejohann)

i) small experimental errors on $|<m>|$ and neutrino masses;

ii) a small value of $\cos 2\theta_{\odot}$;

v) an uncertainty in the NME which accounts to a factor ζ in $|<m>|$, $\zeta \ll (\cos 2\theta_{\odot})^{-1}$.

4 – The see-saw mechanism and Leptogenesis

The see-saw mechanism provides a natural explanation for the smallness of neutrino masses. [Minkovski; Yanagida; Gell-Mann, Ramond, Slansky]

At high energy ($10^9 - 10^{15}$ GeV), RH neutrinos are introduced. They are singlets with respect to the gauge group of the SM and possess very heavy Majorana masses:

$$\boxed{\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N}$$

- **Lepton number is violated.**
- The see-saw mechanism can be embedded in GUT theories.

At low energy, integrating out the heavy neutrinos, the light neutrino masses are naturally small.

$$\mathcal{L} = (\nu_L^T N^T) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ N \end{pmatrix}$$

$$\boxed{\begin{array}{l} M_1 \simeq M_R \\ m_2 \simeq \frac{m_D^2}{M_R} \sim \frac{1\ \mathrm{GeV}^2}{10^9\ \mathrm{GeV}} \sim 1\,\mathrm{eV} \end{array}}$$

In a 3 neutrino mixing, light masses are given by:

$$\boxed{m_\nu = U^* d_m U^\dagger \simeq -Y_\nu^T M_R^{-1} Y_\nu v^2}$$

- Light neutrinos are predicted to be Majorana particles.

Leptogenesis takes place in the context of see-saw models. As the Universe expands, N's go out of equilibrium ($T < M/$ few). Their decays produce a lepton asymmetry, which is then converted into a baryon asymmetry by sphaleron processes. Leptogenesis can succesfully explain the observed baryon asymmetry of the Universe.

[Fukugita, Yanagida; Covi, Roulet, Vissani; Buchmuller, Plumacher]

$$\boxed{\eta_B/s = C\eta_L/s = -10^{-4}\,\epsilon_1}$$

$\boxed{\epsilon_1}$ is the decay asymmetry which depends on the CPV phases:

$$\begin{aligned} \epsilon_1 \quad & \equiv \frac{\Gamma\left(N \to l H\right) - \Gamma\left(N \to l^c H^c\right)}{\Gamma\left(N \to l H\right) + \Gamma\left(N \to l^c H^c\right)} \\ & \propto \sum_j \mathrm{Im}(Y_\nu Y_\nu^\dagger)^2_{1j} \frac{M_j}{M_1} \end{aligned}$$

It requires:

- L violation;
- C and CP violation;
- out of equilibrium.

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It requires:

- L violation; $\boxed{(\beta\beta)_{0\nu}\text{-decay}}$
- C and CP violation;
- out of equilibrium.

5 – Is there a connection between CP-V at low energy and in leptogenesis?

High energy parameters			Low energy parameters		
M_R	3	0	d_m	3	0
Y_ν	9	6	U	3	3

9 parameters are lost, of which 3 phases. In a model-independent way there is **no one-to-one connection** between the low-energy phases and the ones entering leptogenesis.

[see, e.g., S.P., MPLA]

In the biunitary parameterization, $Y_\nu = V_R^\dagger(\beta_1, \beta_2, \beta_3) y V_L(\alpha_1, \alpha_2, \alpha_3)$:

$$\boxed{\begin{aligned} &\epsilon_1(\beta_1, \beta_2, \beta_3) \propto \mathrm{Im}(V_R^\dagger y^2 V_R)^2_{1j} \\ &m_\nu(\alpha_1, \alpha_2, \alpha_3, \beta_1, \beta_2, \beta_3) = V_L^\dagger y V_R M_R^{-1} V_R^T y V_L^* \end{aligned}}$$

[Davidson, Ibarra; Ellis et al.; SP, Petcov, Rodejohann]

- ϵ_1 depends only on the mixing in the right-handed sector.

m_ν depends on all the parameters in Y_ν, both the mixing in the left and right-handed sector.

- Additional information can be obtained in LFV charged lepton decays which depend on V_L.

- **if there is CPV in V_R, we can expect to have CPV in m_ν.**

In many models in which there is a reduced number of parameters,

it is possible to link directly Dirac and Majorana phases to leptogenesis.

- Minimal see-saw model:

If N_3 is much heavier or if there are only two N, the number of parameters is greatly reduced. With additional 2 texture zeros, there is only one phase. It can be shown that:

$$\epsilon_1 \propto \sin 2\delta$$

$$J_{CP} = \mathrm{Im}(Y_{12} Y_{23} Y_{31}) \propto - \sin 2\delta$$

[Frampton, Glashow, Yanagida; Ibarra, Ross]

- Mixing only in the right-handed sector:

$V_L = 1$. In this case the only phases are the ones in V_R.

$$\epsilon_1 = \epsilon_1(\beta_1, \beta_2, \beta_3)$$

$$J_{CP} = \mathrm{Im}(Y_{12} Y_{23} Y_{31}) = J_{CP}(\beta_1, \beta_2, \beta_3)$$

$$\alpha_{21,31} = \alpha_{21,31}(\beta_1, \beta_2, \beta_3)$$

[Branco et al.]

6 – Conclusions

- CPV in the lepton sector can be parametrized by:

1 Dirac phase (measurable in long base-line experiments)

and 2 Majorana phases (one might be determined in $(\beta\beta)_{0\nu}$decay).

- Leptogenesis takes place in the context of see-saw models, which explain

the origin of neutrino masses.

The observation of L violation ($(\beta\beta)_{0\nu}$-decay)

and of CPV in the lepton sector (neutrino oscillations and/or $(\beta\beta)_{0\nu}$-decay)

would be a indication, even if not a proof, of leptogenesis

as the explanation for the observed baryon asymmetry of the Universe.