Neutrinos and CP Violation

XI Internat.Workshop on ”Neutrino Telescopes”

Venezia - 23 February 2005

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1 – Outline

- Theoretical aspects of Dirac and Majorana CPV phases
- Determining the CPV phases in future experiments (long base-line and neutrinoless double beta decay experiments)
- Possible connection between Low energy and High energy (leptogenesis) CP-violation

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).

It is possible to define rephasing invariants associated with CP-V phases.

- $\boxed{J_{CP}}$ is related to the δ phase.

$$\boxed{\begin{aligned} J_{CP} &= \mathrm{Im}(U_{\mathrm{e}1}U_{\mu 2}U^*_{\mathrm{e}2}U^*_{\mu 1}) \\ &= \tfrac{1}{8}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta \end{aligned}}$$

C. Jarlskog ’85; P.I. Krastev and S.T. Petcov ’88

It controls the magnitude of CP and T violating effects in ν-oscillations.

- $\boxed{S_1}$ and $\boxed{S_2}$ are linked to the two Majorana CP-violating phases.

$$\boxed{S_1 = \mathrm{Im}(U_{\mathrm{e}1}U^*_{\mathrm{e}3})} \text{ and } \boxed{S_2 = \mathrm{Im}(U_{\mathrm{e}2}U^*_{\mathrm{e}3})}$$

see e.g., J.F. Nieves and P.B. Pal; J.A. Aguilar-Saavedra and G.C. Branco

They enter in neutrinoless double beta decay (S.M. Bilenky, S.T. Petcov and S.P.).

3 – Measuring CP-V phases

The δ phase

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

A measure of CP- and T- violating effects is provided by the CP and T asymmetries:

$$\begin{aligned} A_{CP} = &\quad P(\nu_l \to \nu_{l'}) - P(\bar{\nu}_l \to \bar{\nu}_{l'}) \\ A_T = &\quad P(\nu_l \to \nu_{l'}) - P(\nu_{l'} \to \nu_l) \end{aligned}$$

In vacuum one has:

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

CP- (T-) 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.

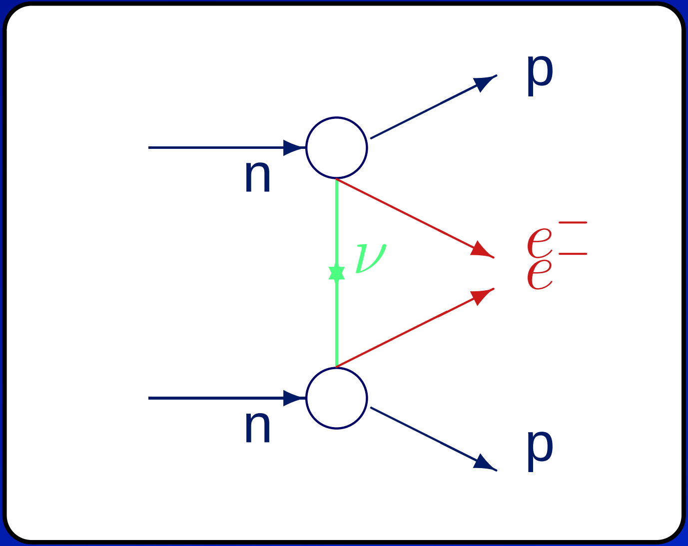
It is necessary to disentangle true CP-V effects due to the δ phase from the ones induced by matter.

Combining different experiments or choosing specific experimental set-ups it is possible in principle to resolve the degeneracies among different parameters and uniquely determine the existence of CP-V in the lepton sector due to the δ phase.

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

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

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

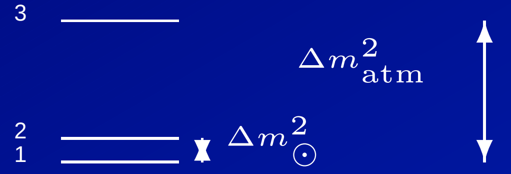
$$\boxed{|{<}\, m\, {>}| \;\equiv \left|\, m_1 |U_{\mathrm{e}1}|^2 + m_2 |U_{\mathrm{e}2}|^2 e^{i\alpha_{21}} + m_3 |U_{\mathrm{e}3}|^2 e^{i\alpha_{31}}\,\right|,}$$

For light neutrinos, $|{<}\, m\, {>}|$ contains all the dependence of $\mathrm{T}_{0\nu}^{1/2}$ on the neutrino parameters.

$U_{\mathrm{e}j}$ are the elements of the lepton mixing matrix U_{PMNS}, m_j the masses of the massive neutrinos ν_j, α_{21} and α_{31} the CP-violating phases.

3 – Measuring CP-V phases

NH spectrum: $m_1 \ll m_2 \ll m_3$

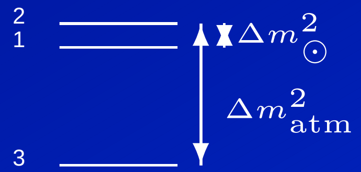


$$|{<}m{>}| \simeq \left|\sqrt{\Delta m^2_\odot}\cos^2\theta_{13}\sin^2\theta_\odot + \sqrt{\Delta m^2_{\rm atm}}\sin^2\theta_{13}e^{i\alpha_{32}}\right|$$

$|{<}m{>}|$ has both an upper and lower bound:

$$\text{few} \times 10^{-4}\ \text{eV} \lesssim |{<}m{>}| \lesssim 8.5 \times 10^{-3}\ \text{eV}$$

IH spectrum: $m_3 \ll m_1 \sim m_2$



$$\sqrt{\Delta m^2_{\rm atm}}\cos 2\theta_\odot \leq |{<}m{>}| \simeq \sqrt{\left(1 - \sin^2(2\theta_\odot)\sin^2\frac{\alpha_{21}}{2}\right)\Delta m^2_{\rm atm}} \leq \sqrt{\Delta m^2_{\rm atm}}$$

$|{<}m{>}|$ has a significant lower bound

$$0.01\ \text{eV} \lesssim |{<}m{>}| \lesssim 0.08\ \text{eV}$$

$|{<}m{>}|$ is in the range of sensitivity of the upcoming $(\beta\beta)_{0\nu}$-decay experiments.

Mass quasi degeneracy (QD)

$m_1 \simeq m_2 \simeq m_3 \equiv m_{\bar{\nu}_e}$

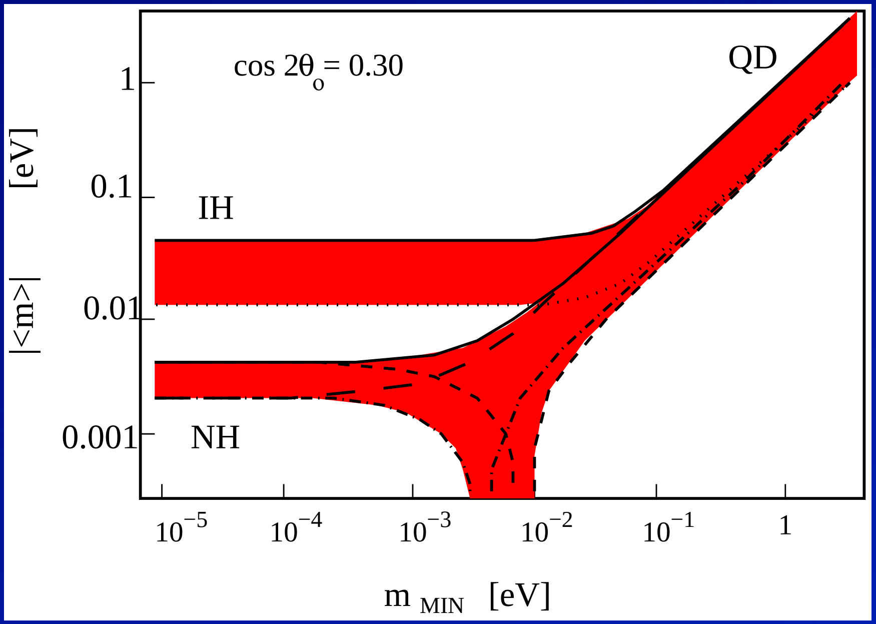
$$\boxed{|{<}m{>}| \simeq m_{\bar{\nu}_e} \left| \left(\cos^2\theta_\odot + \sin^2\theta_\odot e^{i\alpha_{21}} \right) \cos^2\theta_{13} + \sin^2\theta_{13} e^{i\alpha_{31}} \right|}$$

$|{<}m{>}|$ can provide information on m_1, α_{21} and α_{31}.

$|{<}m{>}|$ has both a lower and an upper bound:

$$|{<}m{>}| \gtrsim 0.05 \ \mathrm{eV}$$

All the allowed range for $|{<}m{>}|$ is in the range of sensitivity of present and upcoming $(\beta\beta)_{0\nu}$-decay experiments.



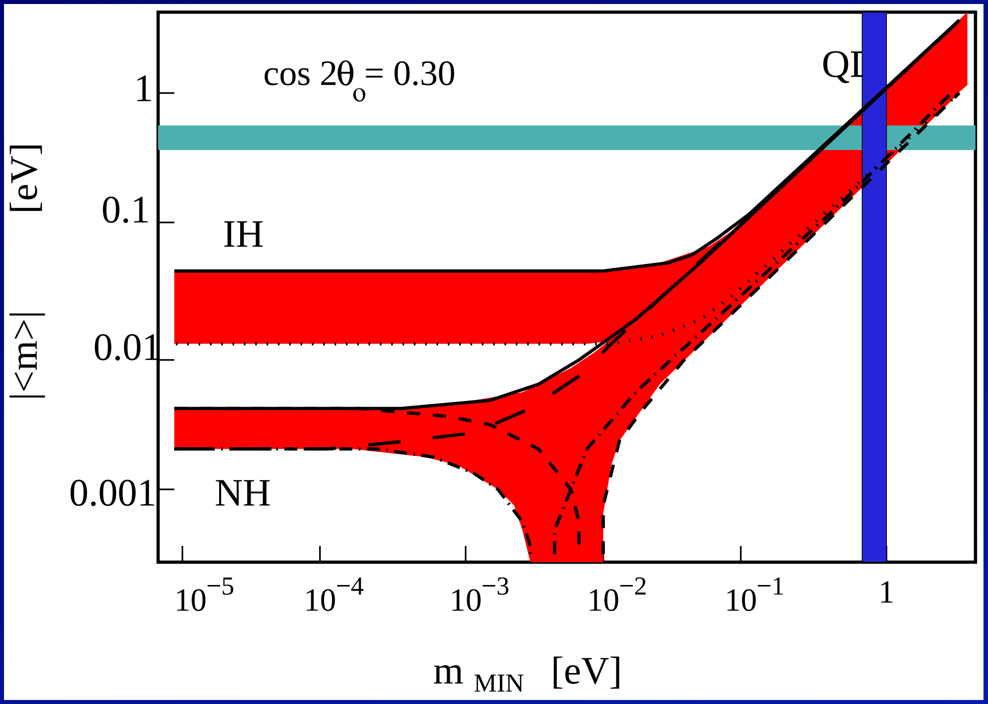
(see S.P., Petcov, PLB2003)

In the case of CPV all the colored regions are allowed.

The red regions denote the “just CPV” regions.

The ”just CPV” region for the IH and QD spectra are larger the smaller $\cos 2\theta_{\odot}$.

3 – Measuring CP-V phases



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

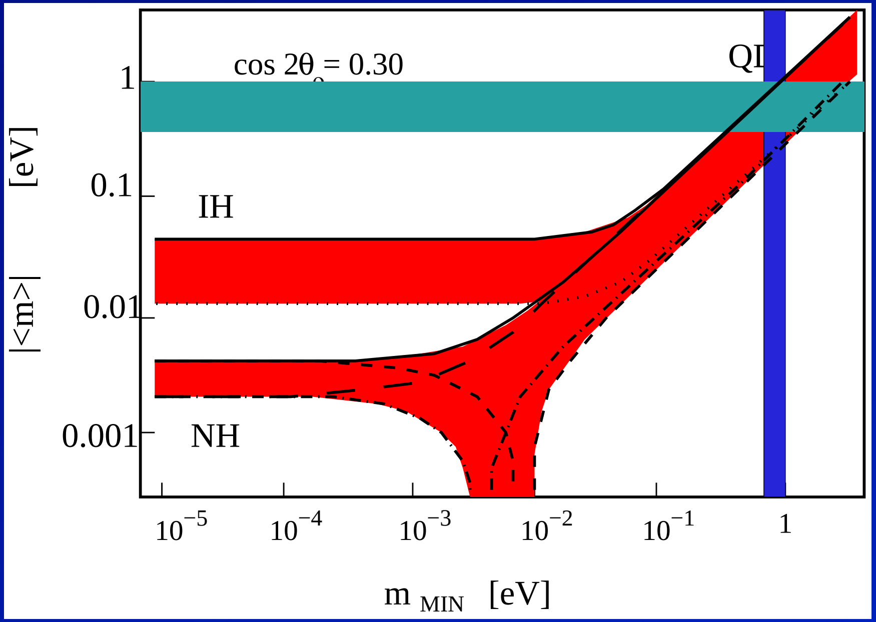
and to constrain the CPV phases,

once the neutrino mass spectrum is known.

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

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

3 – Measuring CP-V phases



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)

Given the predicted values of $|<m>|$, it might be possible only for the IH or QD spectra. In these two cases, the CPV region is inversely proportional to $\cos 2\theta_\odot$.

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 – Low energy CPV and Leptogenesis

In the see-saw mechanism, we introduce RH neutrinos with a very heavy Majorana mass:

$$\boxed{\mathcal{L} = Y_\nu L H N + M_R N N}$$

At low energy, integrating out the heavy neutrinos, the light neutrino masses are naturally small and given by:

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

Leptogenesis takes place in the context of see-saw models. N decay out of equilibrium and 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.

It requires:

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

$$\boxed{\eta_B/s = C\eta_L/s = -10^{-2}\ \epsilon_1\ \kappa}$$

- $\boxed{\kappa \sim 10^{-3} - 10^{-2}}$ is the efficiency factor;
- $\boxed{\epsilon_1}$ is the decay asymmetry which depends on the CPV phases:

$$\boxed{\epsilon_1 \propto \sum_j \mathrm{Im}(Y_\nu^\dagger Y_\nu)^2_{1j}}$$

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 direct connection** between the low-energy phases and the ones entering leptogenesis.

Using the biunitary parameterization, $Y_\nu = V_L^\dagger y V_R$:

$$\epsilon_1 \propto \mathrm{Im}(V_R^\dagger y^2 V_R)^2_{1j}$$
$$m_\nu = V_L^\dagger y V_R M_R^{-1} V_R^T y V_L^*$$

- 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.

- if there is CPV in V_R, we can expect to have CPV in m_ν.
- In models in which there is a reduced number of parameters, it is possible to link directly the Dirac and Majorana phases to the leptogenesis one.
- Additional information can be obtained in LFV charged lepton decays which depend on V_L.

5 – Conclusions

- Establishing CP-V in the lepton sector is a fundamental and challenging task.

- There are:

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

and 2 Majorana phases (one might be determined in neutrinoless double beta decay).

- Leptogenesis takes place in the context of see-saw models, which explain the origin of neutrino masses.

The observation of neutrinoless double beta decay (L violation) and of CPV in the lepton sector would be an indication, even if not a proof, of leptogenesis as the explanation for the observed baryon asymmetry of the Universe.