Do Neutrinos violate CP?

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Summary

- CP Violation in Neutrino Oscillations.
- Dirac or Majorana Neutrinos.
- The case of double beta decay.
- Why is it a challenge
- Connection with Grand-unification scale physics
- Leptogenesys
- Projects: ChoozII, Daya Bay
- Projects: Off beam detectors

Lepton mixing and CP violation

Neutrino mixing opens the way to the possibility of CP and T violation in neutrino oscillations

$$\begin{aligned} CP \text{ violation :} \quad & (\nu_1 \to \nu_2) \neq (\bar{\nu}_1 \to \bar{\nu}_2) \\ T \text{ violation :} \quad & (\nu_1 \to \nu_2) \neq (\nu_2 \to \nu_1) \end{aligned}$$

Finally, we recall that CPT invariance requires that

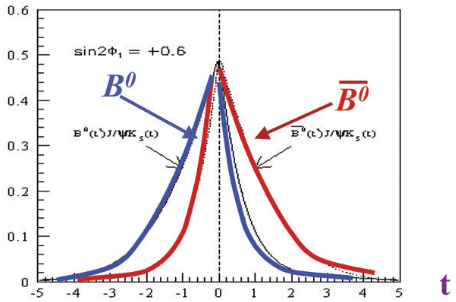
$$CPT \text{ invariance :} \quad (\nu_1 \to \nu_2) = (\bar{\nu}_2 \to \bar{\nu}_1).$$

Disappearence experiments $(\nu_1 \to \nu_1)$ cannot display CP or T violations

N.C., Phys. Lett 72B, 333–335 (1978)

Is comparing ν and $\bar{\nu}$ necessary?

Theoretically we could ascertain T reversal violation by looking at t-odd terms in the oscillation of a single type of neutrinos, $(\nu_1 \to \nu_2)$. This is illustrated by the famous case of $B \to \Psi K_S$.



But one would have to study in precise detail the time development of the oscillations. . . Perhaps with beta-beams?

Dirac vs. Majorana

Neutrinos with non-zero mass reopen the question of the Majorana vs Dirac nature of the neutrinos. Two scenarios are possible: in the first (Dirac) each neutrino flavour would have a left component ν_L that takes part in weak interactions, and a non-weak-interacting right component N_R, thus

Dirac neutrino	$\{\nu_L, N_R\}$
Dirac antineutrino	$\{\bar{N}_R, \bar{\nu}_L\}$

while in the Majorana case one would have ($\bar{\nu}_L$ is *right-handed*)

Majorana	$\{\nu_L, \bar{\nu}_L\}$

Exact conservation of the lepton number remains possible in the Dirac case, while the very presence of mass terms would violate lepton number conservation in the the Majorana case, giving rise, for instance, to the possibility of neutrinoless beta decay.

Majorana Redux

Even if the N_R particles required by the Dirac scheme are present, one would still expect the observable neutrinos to behave as Majorana particles through the so-called see-saw mechanism. Since the N_R particles are singlets with zero hypercharge, nothing in the Standard Model would forbid the presence of a mass term M that directly links the N_R and $\bar{N}_R$. If m_D is the Dirac-like mass that links ν_L to N_R (obtained from the usual Higgs mechanism), one would obtain a Majorana-like link from ν_L to $\bar{\nu}_L$,

$$\nu_L \underset{m_D}{\longrightarrow} N_R \underset{M}{\longrightarrow} \bar{N}_R \underset{m_D}{\longrightarrow} \bar{\nu}_L$$

that would endow the neutrino with a Majorana mass

$$m_\nu = \frac{m_D^2}{M}.$$

Since the Majorana mass M is not constrained by any of the symmetries of the Standard Model one would expect its value to be very large, thus offering a natural explanation for the smallness of the effective neutrino mass m_ν.

From masses to mixing

Mixing arises from the diagonalization of the neutrino mass term. In the Majorana case masses are described by a symmetric matrix $M_{ik} = M_{ki}$, that can be put in diagonal form M_d by a unitary matrix U (L. Maiani, 1981):

$$M_d = U^T \, M \, U$$

1. The matrix U is the lepton mixing matrix. A few phases can be eliminated by redefining the phases of the *charged* leptons.
2. If M is a *real* symmetric matrix, U is a *real* matrix, therefore no CP violation.

The last point is important: CP violation appears in the mixing matrix, but originates in the mass matrix.

The mixing matrix

For the case of three Majorana neutrinos, the lepton mixing matrix U can be written as VK, where V will be parametrized as

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix},$$

while $K = \mathrm{diag}\,(1, e^{i\phi_1}, e^{i(\phi_2+\delta)})$, with $\phi_{1,2}$ the Majorana phases.
At the 3σ level, the allowed ranges are

$$\sin^2(2\theta_{23}) \geq 0.87$$
$$0.70 \leq \sin^2(2\theta_{12}) \leq 0.94$$
$$\sin^2(\theta_{13}) \leq 0.051$$

$$1.4 \times 10^{-3}\ \mathrm{eV}^2 \leq |\Delta m^2_{13}| \leq 3.3 \times 10^{-3}\ \mathrm{eV}^2$$
$$7.1 \times 10^{-5}\ \mathrm{eV}^2 \leq \Delta m^2_{12} \leq 8.9 \times 10^{-5}\ \mathrm{eV}^2.$$

- The Majorana phases do not appear in neutrino oscillations.
- If $\theta_{13} = 0$, δ disappears $\rightarrow$ no CP violation in ν oscillations.

CP Violating phases and double β decay.

Neutrinoless double beta decay experiments are sensitive to the "effective Majorana mass",

$$|m_\nu^{ee}| \equiv \langle m \rangle_{eff}$$
$$= \left| \cos^2\theta_{13} \left(|m_1| \cos^2\theta_{12} + |m_2| e^{2i\phi_1} \sin^2\theta_{12} \right) + \sin^2\theta_{13} |m_3| e^{2i\phi_2} \right| \ .$$

$\langle m \rangle_{eff}$ is sensitive to the Majorana phases, but

1. Uncertainty on the nuclear matrix elements would make it difficult to extract information on $\phi_{1,2}$.
2. In any case only one combination of $\phi_{1,2}$ can be extracted.
3. There may be alternative sources of neutrinoless beta decay.

Neutrinoless beta decay is an enticing challenge, but *CP* violation is not the main motivation.

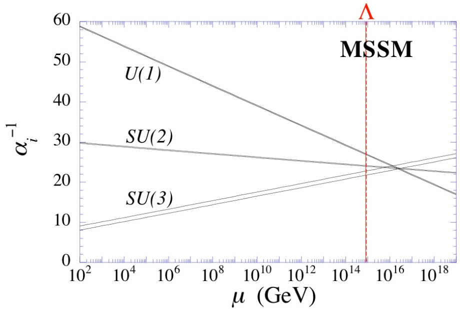
Why CP violation? Why do we care?

We expect CP violation in neutrino physics because it is a generic feature of the mixing phenomenon, as demonstrated in the case of quark mixing by Kobayashi and Maskawa.
Since neutrinos mix we should have CP violation in neutrino oscillations.

CP violation in neutrino oscillations is exciting because:

1. It is a window on physics at the grand unification energy-scale.
2. It is a window on the origin of matter.

The real scale of neutrino masses



The see-saw mechanism indicates that the neutrino mass is determined by physics at the grand-unification energy scale (Graphics from Mohapatra et al. "Theory of Neutrinos", 2004)

The same conclusion is reached if Majorana neutrino masses arise through a double-Higgs interaction,

$$\frac{1}{\Lambda}(\nu H)(\nu H)$$

Either way the neutrino mass term is the only possible $O(\Lambda^{-1})$ extension of the Standard Model.

Why we exist: Leptogenesis

Neutrino oscillations point to the existence of the ultra-heavy N Majorana neutrinos.Through CP violation in their decay these could be the vehicle for the matter-antimatter unbalance in the early univerce that eventually led to the survival of matter in the present era.

Hadrons do not have a comparably direct handle to the very-high energy scale, and CP violation in K-mesons and B-mesons misses by a wide margin the needed asymmetry.

Note however that the very existence of CP violation in neutrino and quark mixing points to the fact that physics at the grand unification scale is itself CP violating. With leptogenesis we are probably only scratching the surface of this aspect of the Universe history, but it is a very nice beginning.

What can we do

There are at many projects at different stages of development that could in the near future impact our knowledge in this field. Two of them involve reactor neutrinos: a second version of the Chooz experiment that established the best existing limit on θ_{13}, and a new experiment at the Daya Bay cluster of power stations in China.

A different approach is offered by higher energy experiments, NOVA in the US and T2K in Japan. A possible experiment at Gran Sasso using an off beam liquid argon detector is also under consideration. These experiments, that look at $\nu_\mu \to \nu_e$ oscillations could in principle be sensitive to the CP violating phase δ, if it (and θ_{13}) is not too small.

Looking further ahead we can expect the final word to be given by new devices such as beta-beams or neutrino factories.

It will take some time before our understanding of CP violation in neutrino oscillations reaches the stage obtained in the corresponding hadronic phenomena.