CP violation due to a Majorana phase in two flavor neutrino oscillations with decays

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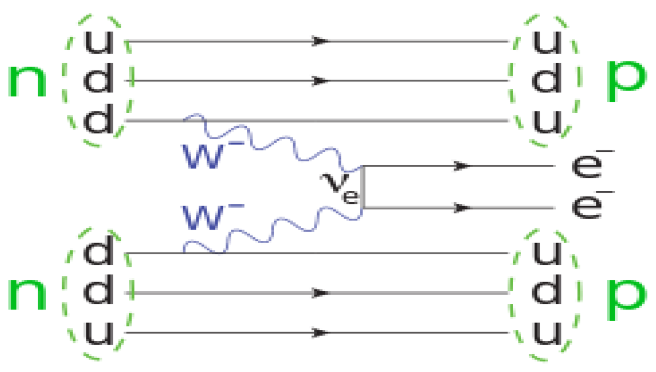
Introduction

- The fundamental nature of most intriguing particle neutrinos, whether they are Dirac or Majorana fermions, is still an open question.
- To probe **Majorana nature**, many experiments looking for signals of neutrinoless double beta decay.



Objective of our work

- Well established fact: Vacuum oscillation probabilities do not depend on the Majorana phases.
- But oscillation probabilities depend on Majorana phases, with an **off-diagonal decoherence** term and also these probabilities are CP-violating.

  F.Benatti *et al.*Phys.Rev.D 64,085015
- The question we ask: **"what are the other possibilities under which the Majorana phases appear in neutrino oscillation probabilities and lead to CP-violation?".**

Oscillations with Decoherence

- Neutrino mass eigenstates ν_i mix via a unitary matrix with flavour states ν_α as

$$\nu_\alpha = U\,\nu_i = O\,U_{ph}\,\nu_i$$

where, $\nu_\alpha = (\nu_e \quad \nu_\mu)^T, \nu_i = (\nu_1 \quad \nu_2)^T$ and

$$O = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \qquad U_{ph} = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\phi} \end{pmatrix}$$

- The evolution of the neutrino considered as an **open system**, can be expressed by the Lidbland–Kossakowski master equation

$$\frac{d\rho}{dt} = -i[H_{eff}, \rho(t)] + D[\rho(t)]$$

$$\begin{pmatrix} \dot\rho_1(t) \\ \dot\rho_2(t) \\ \dot\rho_3(t) \end{pmatrix} = \begin{pmatrix} -\gamma & \Delta-\alpha & 0 \\ \Delta-\alpha & -\gamma & 0 \\ 0 & 0 & -\gamma_3 \end{pmatrix} \begin{pmatrix} \rho_1(t) \\ \rho_2(t) \\ \rho_3(t) \end{pmatrix}$$

$$P_{\mu e} = \frac{1}{2}\Big(1 - e^{-\gamma t}\cos^2(2\theta) - e^{-\gamma t}\sin^2(2\theta) \left[\cosh(\Omega_\alpha t) + \frac{\alpha\sin(2\phi)\sinh(\Omega_\alpha t)}{\Omega_\alpha}\right]\Big)$$

where, α is the off-diagonal decoherence term, $\Delta = \frac{\Delta m^2}{2E}$ and $\Omega_\alpha = \sqrt{\alpha^2 - \Delta^2}$.

$\implies$ The Majorana phase appears in probability expression due to decoherence as long as the **off-diagonal term** $\alpha \neq 0$.

$$\Delta_{CP}(t) = P_{\mu e}(t) - P_{\bar\mu\bar e}(t) = -e^{-\gamma t}\sin^2(2\theta)\frac{\alpha\sin(2\phi)\sinh(\Omega_\alpha t)}{\Omega_\alpha}$$

Oscillations with decay-Hamiltonian

- The general decay-Hamiltonian

$$\mathcal{H} = M - i\Gamma/2,$$

$$M = \begin{pmatrix} a_1 & 0 \\ 0 & a_2 \end{pmatrix}, \quad \Gamma/2 = \begin{pmatrix} b_1 & \frac{1}{2}\eta e^{i\xi} \\ \frac{1}{2}\eta e^{-i\xi} & b_2 \end{pmatrix}$$

System of two particles which can oscillate into each other, these matrices can have off-diagonal terms, as in the case of neutral meson system.

- The matrix Γ needs to be positive semi-definite, *i.e.*, **non negative** $\implies$ $b_1, b_2 \geq 0$ and $\eta^2 \leq 4b_1 b_2$.
- The mass eigenstates are **not** decay eigenstates ($\eta \neq 0$) and evolution equation:

$$i\frac{d}{dt}\nu_\alpha(t) = \Big[\frac{(a_1+a_2)}{2}\sigma_0 - \frac{(a_2-a_1)}{2}O\sigma_z O^T - \frac{i}{2}(b_1+b_2)\sigma_0 - \frac{i}{2}OU_{ph}(\vec\sigma.\vec\Gamma)U_{ph}^\dagger O^T\Big]\nu_\alpha(t)$$

where $\vec\Gamma = [\eta\cos\xi, -\eta\sin\xi, -(b_2-b_1)]$.

- Since σ_x and σ_y do not commute with U_{ph} matrix, the Majorana phase ϕ **remains** in the evolution equation.

Oscillation Probability

- Time evolution operator in the mass eigenbasis is $\mathcal{U} = e^{-i\mathcal{H}t}$, can be expanded in the basis spanned by σ_0 and Pauli matrices.

$n_\mu \equiv (n_0, \vec n)$, $n_\mu = Tr[(-i\mathcal{H}t).\sigma_\mu]/2$.

$$\mathcal{U} = e^{n_0}\left[\cosh n\;\sigma_0 + \frac{\vec n.\vec\sigma}{n}\sinh n\right],$$

$$n = \sqrt{n_x^2 + n_y^2 + n_z^2}$$

- Oscillation probabilities can be obtained as

$$P_{\alpha\beta} = |(\mathcal{U}_f)_{\alpha\beta}|^2, \quad \mathcal{U}_f = U\mathcal{U}U^{-1}$$

- In the limit $b_1 = b = b_2$ and $\eta \ll |a_2 - a_1|$,

$$P_{ee} = e^{-2bt}\left(P_{ee}^{\rm vac} - \eta\cos(\xi-\phi)\mathcal{A}\right)$$
$$P_{\mu\mu} = e^{-2bt}\left(P_{\mu\mu}^{\rm vac} + \eta\cos(\xi-\phi)\mathcal{A}\right)$$
$$P_{e\mu} = e^{-2bt}\left(P_{e\mu}^{\rm vac} + 2\eta\sin(\xi-\phi)\mathcal{B}\right)$$
$$P_{\mu e} = e^{-2bt}\left(P_{\mu e}^{\rm vac} - 2\eta\sin(\xi-\phi)\mathcal{B}\right).$$

where, $\mathcal{A} = \dfrac{\sin(2\theta)\sin[(a_2-a_1)\,t]}{(a_2-a_1)}$,

$$\mathcal{B} = \frac{\sin(2\theta)\sin^2\left[\frac{1}{2}t(a_2-a_1)\right]}{(a_2-a_1)}$$

CP-violation

- We assume CPT-conservation which implies

$$\bar M = M \text{ and } \bar\Gamma = \Gamma^*.$$

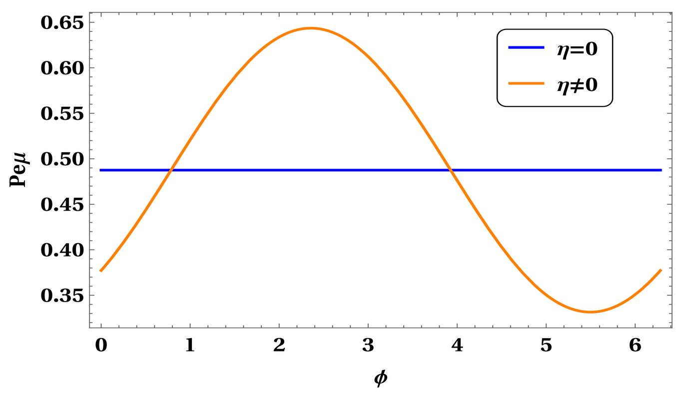
- For antineutrino probabilities, substitute $\phi \to -\phi$ and $\xi \to -\xi$.

$$P_{\bar e\bar\mu} \neq P_{e\mu} \implies \text{CP-violation}$$

$$P_{e\mu} \neq P_{\mu e} \implies \text{T-violation}$$

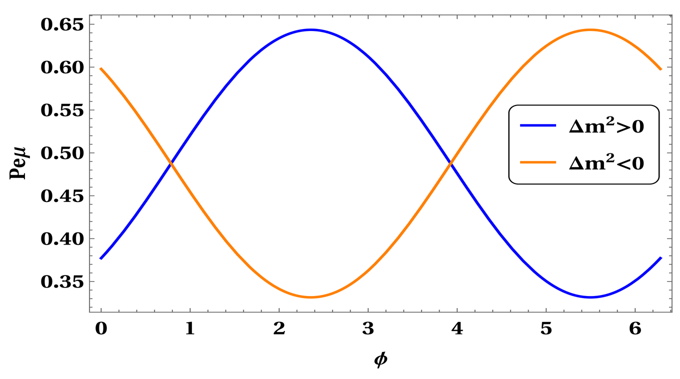
Results and Discussions

- When decay eigenstates **are not aligned** with the mass eigenstates (off-diagonal term in Γ), probability expressions are sensitive to Majorana phase ϕ.



- Presence of η **violates** the equalities $P_{\mu\mu} = P_{ee}$ and $P_{\mu e} = P_{e\mu}$ that we see in the case of two flavour vacuum oscillations.
- The terms with $\mathcal{B}$, present in oscillation probabilities, have opposite signs for the two cases: $a_2 > a_1$ ($m_2 > m_1$) and $a_2 < a_1$ ($m_2 < m_1$).

  $\implies$ Oscillation probability (Not the survival probability) is sensitive to **mass hierarchy**.



Different types of CP-violation are possible:

→ due to the Majorana phase ϕ which we call CP-violation in mass.
→ due to the phase ξ of Γ_{12} which we call CP-violation in decay.
→ most general possibility is $\eta \neq 0$, $\xi \neq 0$ and $\phi \neq 0$. In this case, we have CP-violation due to both mass and decay provided $\phi \neq \xi$.

- In two special cases, when ϕ = ξ or when ϕ = $\xi = 0$, there is **no CP-violation** even if $\eta \neq 0$. In such a situation, the flavour conversion probabilities are insensitive to off-diagonal elements of Γ but the flavour survival probabilities do depend on them.

Observational effects

- Supernova 1987A, $\tau_\nu \geq 5.7 \times 10^5$s (m_ν/eV)
  $\implies$ $\Gamma_\nu \equiv b \approx 10^{-21}$ eV for $m_\nu \sim 1$ eV

  J.A.Frieman *et al.* Phys.Lett.B 200(1988)
- The new effects considered in this work are of order $\eta/(a_2 - a_1) = \eta E/\Delta m^2$. These effects are of order 10% for $\Delta m^2 \approx 10^{-4}\,\text{eV}^2$ if $E \approx 10^7$ GeV.
- Ultra high energy neutrinos from **astrophysical sources** provide a platform to study the effect.

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Reference

A.K. Pradhan *et al.* Phys. Rev. D 107, 013002

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