

Appearance of Majorana phase in two flavor neutrino oscillations with neutrino decay

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In collaboration with **S. Uma Sankar, K. Dixit**

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HIDDe

Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Asymmetry

Essential Asymmetries of Nature

Motivation



- ➔ Oscillation probabilities depend on Majorana phases for **neutrino decoherence**, with an off-diagonal term in decoherence matrix.

F. Benatti et al. Phys.Rev.D 64(2001),085015
A. capolupo et al. Phys. Lett. B 7929(2019) 298-303

- ➔ Towards distinguishing Dirac from Majorana with **Gravitational waves**.

Stephen S. King et al. 2306.05389

Our Proposal

→ The **decay-Hamiltonian** $\mathcal{H} = M - i\Gamma/2,$

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

$$a_1 = m_1^2/2E \text{ and } a_2 = m_2^2/2E$$

→ The time evolution operator for neutrinos in the mass eigenbasis is $\mathcal{U} = e^{-i\mathcal{H}t}$

$$n_\mu = \text{Tr}[(-i\mathcal{H}t) \cdot \sigma_\mu] / 2 \quad \mathcal{U} = e^{n_0} \left[\cosh n \sigma_0 + \frac{\vec{n} \cdot \vec{\sigma}}{n} \sinh n \right]$$

• In flavor basis

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

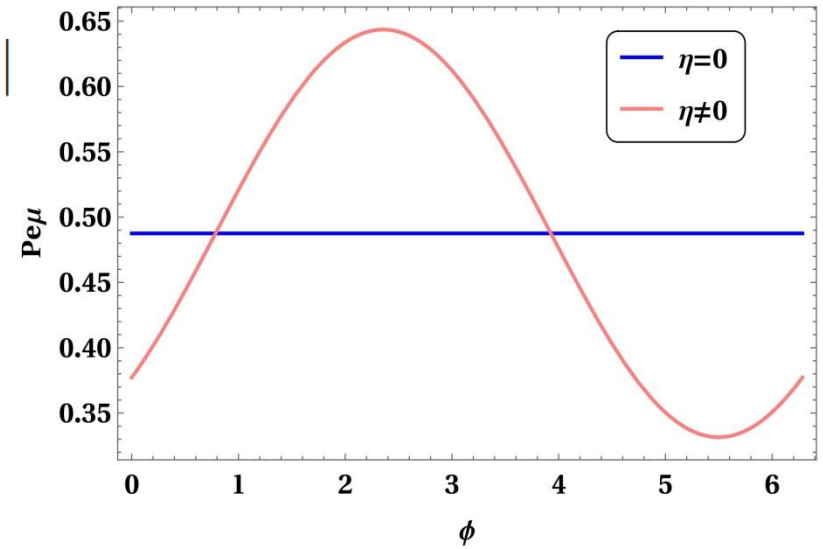
Outcomes

In the limit

$$b_1 = b = b_2 \text{ and } \eta \ll |a_2 - a_1|$$

$$P_{e\mu} = e^{-2bt} (P_{e\mu}^{\text{vac}} + 2\eta \sin(\xi - \phi)\mathcal{B})$$

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



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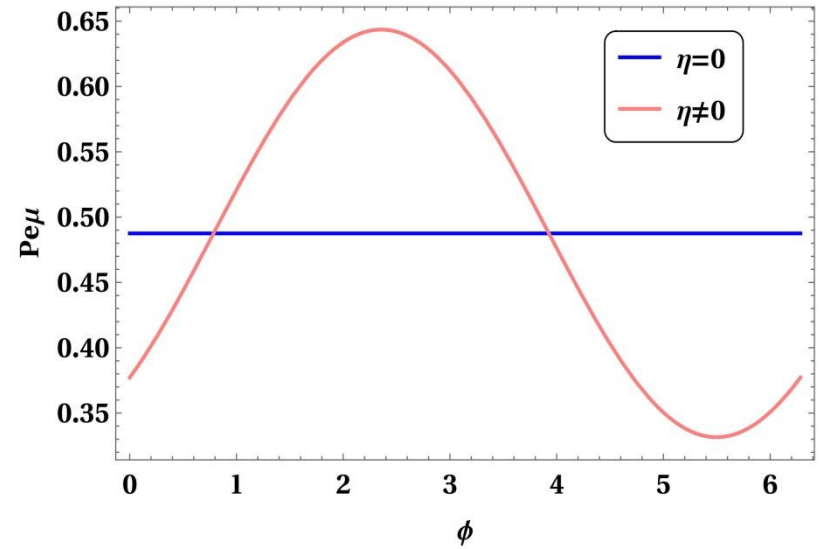
CPT Conservation $\bar{M} = M$ and $\bar{\Gamma} = \Gamma^*$

↓ $\phi \rightarrow -\phi \quad \xi \rightarrow -\xi$

$$P_{\bar{e}\bar{\mu}} = e^{-2bt} (P_{\bar{e}\bar{\mu}}^{\text{vac}} - 2\eta \sin(\xi - \phi)\mathcal{B})$$



CP Violation $P_{\bar{e}\bar{\mu}} \neq P_{e\mu}$



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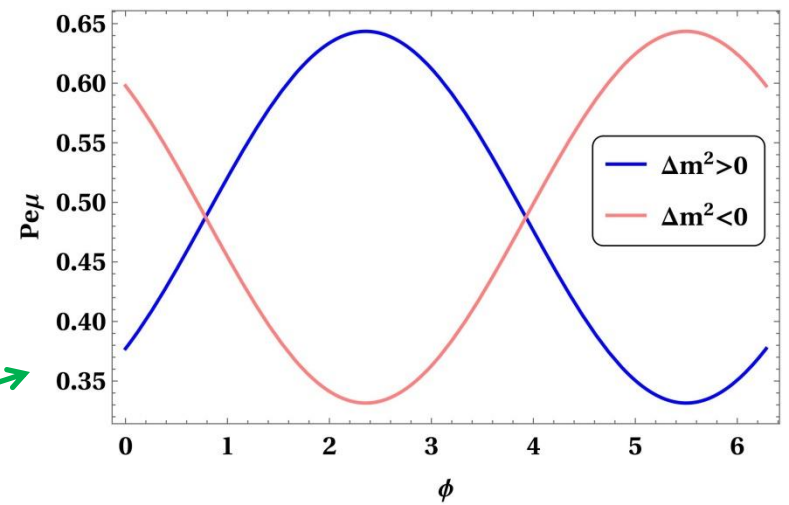
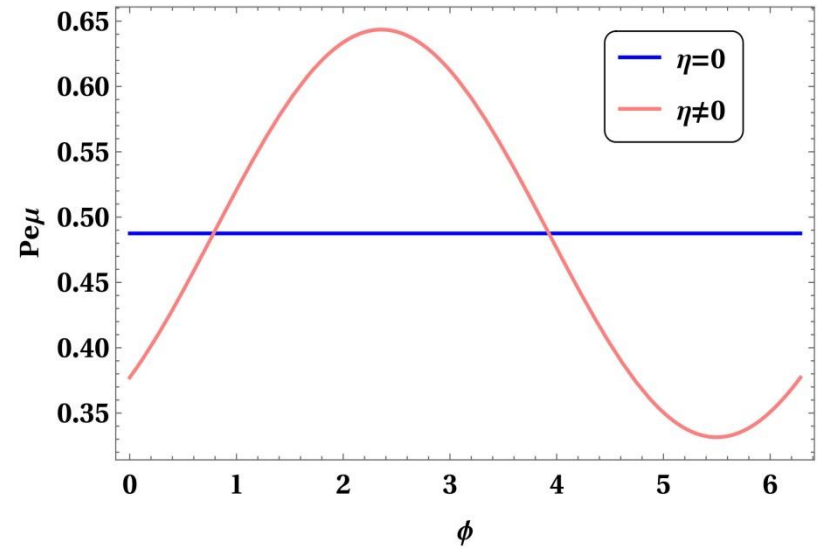
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↓ **CP Violation** $P_{\bar{e}\bar{\mu}} \neq P_{e\mu}$

Sensitive to Mass Hierarchy



Do we ever observe this effect ??

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

J.A.Frieman et al. Phys.Lett.B 200(1988) 115-121

The new effects considered in this work are of order

$$\eta / (a_2 - a_1) = \eta E / \Delta m^2$$

- Effects are of **order 10%** for $\Delta m^2 \approx 10^{-4} \text{ eV}^2$ if **$E=10^7 \text{ GeV}$**

★ **Ultra high energy neutrinos** from astrophysical sources provide a platform to study the effect.

Thank you for your attention

Appearance of Majorana phase in two flavour neutrino oscillations with neutrino decay

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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 $n\beta\beta$ double beta decay.

Source: wikipedia

The matrix Γ needs to be positive semi-definite, i.e., **non negative** $\Rightarrow b_1, b_2 \geq 0$ and $\eta^2 \leq 4b_1b_2$.

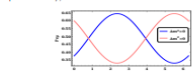
- The mass eigenstates are **not** decay eigenstates ($\eta \neq 0$) and evolution equation:

$$\frac{d}{dt} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \left[\frac{(a_1 + a_2)}{2} \sigma_3 - \frac{(a_2 - a_1)}{2} O \sigma_1 O^T - \frac{(b_1 + b_2) \sigma_3 - 2OU_{\beta\beta}(\theta, \Gamma)U_{\beta\beta}^T O^T}{2} \right] \nu_e(t)$$

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

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

- The terms with B present in oscillation probabilities, have opposite signs for the two cases $a_1 > a_2$ ($m_2 > m_1$) and $a_1 < a_2$ ($m_2 < m_1$). \Rightarrow Oscillation probability (Not the survival probability) is sensitive to **mass hierarchy**.



Objective of our work

- Well established fact: Vacuum oscillation probabilities do not depend on the Majorana phases.
- The oscillation probabilities depend on Majorana phases for neutrino decoherence, with an off-diagonal term and also these probabilities are CP -violating.
- The question we ask: **What are the other possibilities under which the Majorana phases appear in neutrino oscillation probabilities and lead to CP -violation?**

Vacuum neutrino oscillations

- Neutrino mass eigenstates ν_i mix via a unitary matrix with flavour states ν_{α} as $\nu_{\alpha} = U_{\alpha i} \nu_i = O U_{\beta\beta} U_{\alpha i}$ where, $\nu_{\alpha} = (\nu_e, \nu_{\mu})^T, \nu_i = (\nu_1, \nu_2)^T$ and $O = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}, U_{\beta\beta} = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\phi} \end{pmatrix}$
- The traditional diagonal Hamiltonian in mass-basis that governs the time evolution of neutrino mass eigenstates $\mathcal{H} = \begin{pmatrix} a_1 & 0 \\ 0 & a_2 \end{pmatrix} = \frac{(a_1 + a_2)}{2} \sigma_3 + \frac{(a_2 - a_1)}{2} \sigma_1$ where, $a_i = m_i^2/2E$ and $a_{\beta} = m_{\beta}^2/2E$.
- In flavour basis, evolution Hamiltonian becomes $H_{\alpha} = \frac{(a_1 + a_2)}{2} \sigma_3 - \frac{(a_2 - a_1)}{2} OU_{\beta\beta} \sigma_1 U_{\beta\beta}^T O^T$
- Since, $U_{\beta\beta}$ and σ_x are diagonal matrices they commute and σ_x term simplifies to $O \sigma_1 O^T$ and the phase ϕ **disappears** from the evolution equation.
- Also Majorana phases do not appear for the **matter effects** (pure SM interactions or nonstandard interactions).

Oscillations with decay-Hamiltonian

- The general decay-Hamiltonian $\mathcal{H} = M - i\Gamma/2, M = \begin{pmatrix} a_1 & 0 \\ 0 & a_2 \end{pmatrix}, \Gamma/2 = \begin{pmatrix} b_1 & 0 \\ 0 & b_2 \end{pmatrix}$

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.

Evolution Operator and Probabilities

- Time evolution operator in the mass eigenbasis is $U = e^{-i\mathcal{H}t}$, can be expanded in the basis spanned by σ_x and Pauli matrices.
- $n_{\alpha} \equiv (n_{\alpha}, \bar{n}_{\alpha}), n_{\alpha} = Tr[(i\mathcal{H}t)\sigma_{\alpha}]/2$
- $U = e^{-i} \left[\cosh n \sigma_3 + \frac{\Gamma_{\beta\beta}}{n} \sinh n \right]$
- $n = \sqrt{n_2^2 + n_1^2 + n_3^2}$
- Oscillation probabilities can be obtained as $P_{\alpha\beta} = |\langle U_{\beta\beta} \nu_{\alpha} | U_{\beta\beta} \nu_{\alpha} \rangle|^2, U_{\beta\beta} = U U U^{-1}$
- In the limit $b_1 = b_2 = b$ and $\eta \ll |a_2 - a_1|$, $P_{\nu_e \nu_e} = e^{-2\mathcal{B}} (P_{\nu_e \nu_e}^{\text{vac}} - \eta \cos(\xi - \phi)A)$
 $P_{\nu_e \nu_{\mu}} = e^{-2\mathcal{B}} (P_{\nu_e \nu_{\mu}}^{\text{vac}} + \eta \cos(\xi - \phi)A)$
 $P_{\nu_{\mu} \nu_e} = e^{-2\mathcal{B}} (P_{\nu_{\mu} \nu_e}^{\text{vac}} + 2\eta \sin(\xi - \phi)B)$
 $P_{\nu_{\mu} \nu_{\mu}} = e^{-2\mathcal{B}} (P_{\nu_{\mu} \nu_{\mu}}^{\text{vac}} - 2\eta \sin(\xi - \phi)B)$
 where, $A = \frac{\sin(2\theta) \sin^2 \frac{\Delta}{2} (a_2 - a_1)}{(a_2 - a_1)}$
 $B = \frac{\sin(2\theta) \sin^2 \frac{\Delta}{2} (a_2 - a_1)}{(a_2 - a_1)}$

CP-violation

- We assume CP -conservation which implies $M = M^T$ and $\Gamma = \Gamma^T$.
- For antineutrino probabilities, substitute $\phi \rightarrow -\phi$ and $\xi \rightarrow -\xi$.
- $P_{\nu_e \nu_e} \neq P_{\bar{\nu}_e \bar{\nu}_e} \Rightarrow$ **CP-violation**
- $P_{\nu_e \nu_{\mu}} \neq P_{\nu_{\mu} \nu_e} \Rightarrow$ **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 .

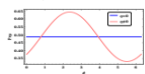


Figure 1. $P_{\alpha\beta}$ as a function of ϕ .

- Presence of η **violates** the equalities $P_{\nu_e \nu_e} = P_{\bar{\nu}_e \bar{\nu}_e}$ and $P_{\nu_e \nu_{\mu}} = P_{\nu_{\mu} \nu_e}$ that we see in the case of two flavour vacuum oscillations.

Observational effects

- Supernova 1987A, $\nu_{\mu} \geq 5.7 \times 10^5$ (m_{ν}/eV) $\Rightarrow \Gamma_{\mu} \approx 10^{-21}$ eV for $m_{\nu} \sim 1$ eV. (A. Frieman et al. Phys. Lett. B 2001/988)
- The new effects considered in this work are of order $\eta/(a_2 - a_1) \approx \eta E/\Delta m^2$. These effects are of order 10% for $\Delta m^2 \approx 10^{-4} \text{eV}^2$ if $E \approx 10^7$ eV.
- Ultra high energy neutrinos from **astrophysical sources** provide a platform to study the effect.

Conclusions

- We have shown that, in addition to the off-diagonal dissipator matrix, the **off-diagonal decay matrix** is another possible source for the appearance of Majorana phases in the oscillation probabilities and the corresponding CP -violation.
- We point out another interesting result that the CP -violating term in the oscillation probability is also **sensitive to the neutrino mass ordering**.
- We have given a short discussion on the values of parameters for which the effects described in this work are likely to be observable.
- The extension of this work for three flavour oscillations is straightforward.

Acknowledgements

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Reference

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

For any discussions come to my poster #7

Invisibles23 Workshop, Göttingen

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