Decoherence Effects On Neutrino Oscillation Probabilities

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Introduction

Neutrinos propagating through matter behaves like an open-quantum system. These neutrinos interact with the environment via weak coupling, and this leads to a loss of coherence between the neutrino mass states. We generally observe this phenomenon of decoherence in systems interacting with a dissipative environment. This interaction also affects the neutrino oscillation probabilities. In this present work, we explore the influence of environmental decoherence on the oscillation probabilities.

We consider neutrino system as an open-quantum system and apply the Lindblad Master equation to study the time evolution of the neutrino states. We are working on a framework that will give out the neutrino oscillation probabilities by solving the Lindblad Master equation, taking into account the environmental decoherence. We then study the potential effect of decoherence on the oscillation probabilities for the long baseline sector.

Formalism

- The Hamiltonian describing the neutrinos in a closed system is given by-

$$\hat{H}_M = \hat{H}_v + \hat{V}_{matter} \tag{1}$$

where the vacuum Hamiltonian is $H_\nu = diag(E_1, E_2, E_3)$ and the matter potential is $V_{matter} = diag(A, 0, 0)$

- Transforming the Hamiltonian to an effective mass basis-

$$\hat{H} = \frac{1}{2E_\nu} diag(\tilde{E}_1, \tilde{E}_3, \tilde{E}_3) \tag{2}$$

- Upon rephasing the Hamiltonian, we get-

$$\hat{H} = \frac{1}{2E_\nu} diag(0, \Delta\tilde{m}^2_{21}, \Delta\tilde{m}^2_{31}) \tag{3}$$

- Rexpressing the Hamiltonian in the form -

$$\hat{H} = 2\Delta diag(0, \tilde{\chi}_-, \tilde{\chi}_+) \tag{4}$$

with $\tilde{\chi}_\pm = \frac{1}{2}[\hat{A} + 1 \pm \tilde{\chi}_0]$, $\tilde{\chi}_0 = \sqrt{1 + \hat{A}^2 - 2\hat{A}cos2\theta_{13}}$

and $\hat{A} = \pm\frac{\sqrt{2}G_F n_e}{2\Delta}$, is the matter potential.

Using Equation 3 and 4, we get-

$$\tilde{\Delta}_{12} = \Delta\tilde{\chi}_-, \tilde{\Delta}_{13} = \Delta\tilde{\chi}_+, \tilde{\Delta}_{23} = \Delta\tilde{\chi}_0$$

We use these definitions and derived relations along with the density matrix formalism to study the time evolution of neutrinos in presence of decoherence.

Phenomenological Model

- The time evolution of ν in closed system can be studied using Von Neumannn equation.
- Systems open to the environment can be studied using Lindblad Master equation.
- In this framework, we treat neutrinos as open quantum system interacting with the environment, in presence of matter potential.
- We study the evolution of $\nu's$ in time by using the density matrix ρ_ν and the calculate the oscillation probabilities.

Density matrix formalism

- We model the neutrinos as open quantum system and use the density matrix in the form given by

$$\rho_\nu = \sum_i \rho_{ij} |\nu_i\rangle \langle\nu_j| \tag{5}$$

- The effect of environmentally induced decoherence is introduced by adding a dissipator term to the Von Neumann equation. We use this new "Lindblad Master equation" for studying time evolution of 3-flavor neutrino system.

$$\frac{d}{dt}\rho_\nu(t) = -i[H, \rho_\nu(t)] - D[\rho_\nu(t)] \tag{6}$$

with the dissipator term as,

$$D[\rho_\nu(t)] = \sum_n [\{\rho_\nu(t), D_n^+ D_n\} - 2D_n \rho_\nu(t) D_n^+]$$

- Constraints like increase of entropy with time and conservation of average energy of the system are imposed on D_n which reduces the dissipator term to

$$D[\rho_\nu(t)] = \begin{pmatrix} 0 & \Gamma_{21}\rho_{12}(t) & \Gamma_{31}\rho_{13}(t) \\ \Gamma_{21}\rho_{21}(t) & 0 & \Gamma_{32}\rho_{23}(t) \\ \Gamma_{31}\rho_{31}(t) & \Gamma_{32}\rho_{32}(t) & 0 \end{pmatrix} \tag{7}$$

Here, Γ_{ij} are decoherence couplings.

- We investigate for the probability channel ($\nu_\mu \rightarrow \nu_e$) and integrate equation (6) to obtain the time evolved density matrix,

$$\rho^\mu(t = L) = \begin{pmatrix} |U_{\mu 1}|^2 & U_{\mu 1}U^*_{\mu 2}e^{-\omega^*_{21}L} & U_{\mu 1}U^*_{\mu 3}e^{-\omega^*_{31}L} \\ U_{\mu 2}U^*_{\mu 1}e^{-\omega_{21}L} & |U_{\mu 2}|^2 & U_{\mu 2}U^*_{\mu 3}e^{-\omega^*_{32}L} \\ U_{\mu 3}U^*_{\mu 1}e^{-\omega_{31}L} & U_{\mu 3}U^*_{\mu 2}e^{-\omega_{32}L} & |U_{\mu 3}|^2 \end{pmatrix} \tag{8}$$

where, $\omega_{ij} = \Gamma_{ij} + 2i\tilde{\Delta}_{ij}$

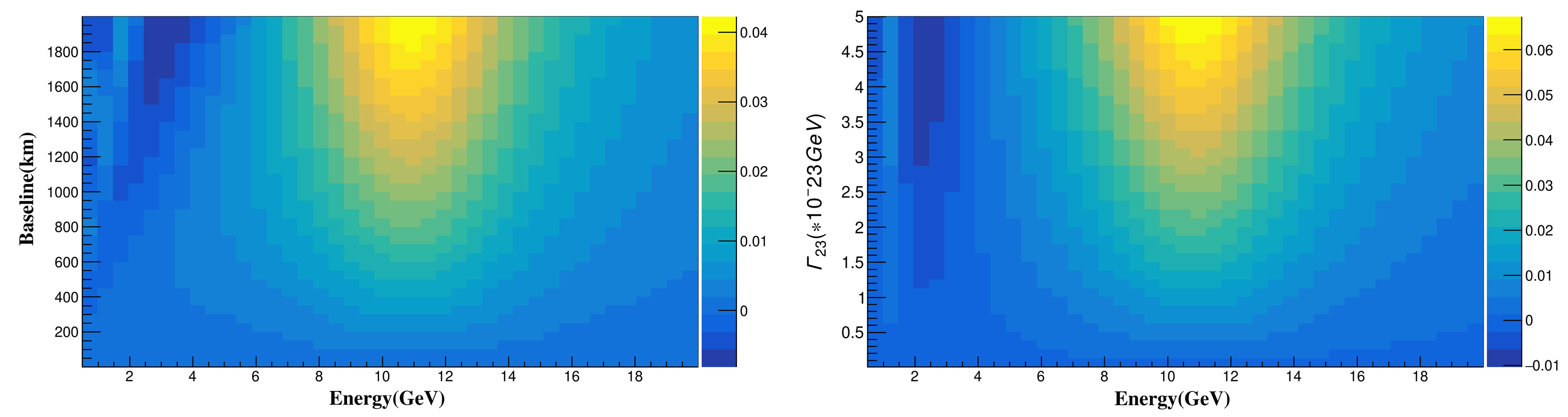
- The ν_e appearance probability is calculated to be

$$P(\nu_\mu \rightarrow \nu_e) = \sum_{i,j} U_{ei}U^*_{ej}[\rho^\mu_{ij}(t)]_{ij} \tag{9}$$

Results

- We define,

$$\Delta P_{\alpha\beta} = P_{\alpha\beta}(With\ \ Decoherence) - P_{\alpha\beta}(Without\ \ Decoherence)$$



(a) Plot of Energy vs L with $\Gamma = 2 * 10^{-23}GeV$ (b) Plot of Energy vs Gamma Γ with L=1300km

Figure 1. Plots of ΔP

- The decoherence effect is observed to be significant for intermediate energy range $(9 - 13GeV)$ and for baseline $> 1000km$.
- We also observe some effects at lower baselines at energy around $11GeV$.

Concluding Remarks

- We developed an algorithm to calculate the oscillation probabilities by incorporating the effect of decoherence.
- We explored the change of probabilities for a range of Γ values.
- In future, we will explore different experiments and study their sensitivites towards decoherence.

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References

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