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Study of Neutrino Oscillation and Dissipative Effects in LBNE

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Abstract

In this work we make a brief phenomenological study for three neutrino oscillation taking into account the matter effect from the open quantum system approach. Open quantum system approach has a rigorous set of the statements and when it is applied on neutrino oscillation, due to dissipative phenomena, the neutrinos may exhibit new and peculiar effects, in special, decoherence and relaxation effects. We use the most effective quantum dissipators and we study how change the neutrino behavior considering the LBNE configuration. In particular, we show how each kind of dissipative effect is linked to each mixing angle and consequently, as the new effects are described in the survival and appearance probabilities. Interesting enough, in the LBNE case we present a new behavior at matter resonance region that can be seen even when the dissipative effect is small compared with energy dependent oscillation parameters.

Keywords: LBNE, Dissipative effects, Neutrino Oscillation

1. Introduction

The neutrino oscillation model is modified when we consider neutrinos like a non isolated system. We use an open quantum system approach following the Lindblad Master Equation [1, 2] to obtain neutrino oscillation probabilities with dissipation effects.

We show some results for LBNE configuration that is a experiment where the matter effect is import [3, 4] and by treating the neutrinos like an open quantum system [2], we can use the effective mixing angle mapping made by Ref. [5] and the result that appears in Ref. [6] to show how the neutrino probabilities change due to dissipative effects.

2. Overview of Formalism and Results Preliminary

We consider that neutrinos can be evolved by means of the Lindblad Master Equation that is written as

$$\frac{d\rho_\nu(t)}{dt} = -i[H_{osc}, \rho_\nu(t)] + D[\rho_\nu(t)]\,, \qquad (1)$$

where H_{osc} is a piece of the total Hamiltonian that can be given by $H_{tot} = H_{osc} + H_R + H_{int}$, such that,

$$H_{osc} = H_{mass} + H_{matter}\,, \qquad (2)$$

and it can be expressed as $H_{osc} = diag.\{\tilde{E}_1, \tilde{E}_2, \tilde{E}_3\}$ if we consider the effective mass basis. This becomes similar the formalism to the neutrino oscillation with dissipative effects considering its propagation being in constant matter or in vacuum [6].

The dissipative part can be written as

$$D[\rho_\nu] = \frac{1}{2}\sum_{k=1}^{N^2-1}\left(\left[V_k, \rho_\nu V_k^\dagger\right] + \left[V_k\rho_\nu, V_k^\dagger\right]\right), \qquad (3)$$

where the operators V_k act on neutrinos state only and must be such that $\sum_k V_k^\dagger V_k = \mathbb{1}$ for the trace of ρ_ν to be preserved.

The evolution with the equation (1), where the term $D[\rho]$ is given by (3), only converts a density matrix into density matrix if the time evolution is complete positive. The concept of complete positivity constrains the evolution where, it is kept inside of the physical space of Hilbert and even the evolution transforming pure states

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into mixed states due to dissipation effects and the quantum interpretation is satisfied [7]. We can make the Von Neumann entropy, $S = -Tr[\rho_\nu \ln \rho_\nu]$, increases with time (or distance in the current case) during the process of taking a pure state into a mixed state. To this end, we must ensure that $V_k^\dagger = V_k$ [8].

The Eq. (1) can be expanded in matrix basis of the $SU(3)$ such that it assumes the following form

$$\dot{\rho}_\vartheta \lambda_\vartheta = f_{ijk} H_i \rho_j \lambda_\vartheta \delta_{\vartheta k} + \rho_\nu D_{\vartheta \nu} \lambda_\vartheta \,, \qquad (4)$$

and the additional matrix, $D_{\mu\nu}$, must be real, symmetric and positive definite. By complete positivity, we have 36 phenomenological parameters bounded among each other with inequalities which guarantee the positivity. We can use some suitable physical constraint in order to realize each dissipative effect as well as reduce physically the number of the new phenomenological parameters.

One constraint is obtained supposing the decoherence is a odd phenomenon and distinguishable of the other dissipative phenomena. So, if we put the constrint $Tr[H\rho(t)] = 0$, only decoherence effect will be present on our interesting subsystem. This constraint ensure that the energy is conserved inside of interest subsystem and the form of the quantum dissipation is given by

$$D_{\mu\mu} = -diag\{0, \Gamma_{21}, \Gamma_{21}, 0, \Gamma_{31}, \Gamma_{31}, \Gamma_{32}, \Gamma_{32}, 0\} \,. \qquad (5)$$

On the other hand, we can break this symmetry putting non zero values in the entries D_{33} and D_{88}. As by means of complete positivity, the entries in the principal main diagonal must be bigger that the off ones, therefore, this is the most effective quantum dissipator and it can be written as

$$D_{\mu\mu} = -diag\{0, \Gamma_{21}, \Gamma_{21}, \Gamma_{33}, \Gamma_{31}, \Gamma_{31}, \Gamma_{32}, \Gamma_{32}, \Gamma_{88}\} \,. \qquad (6)$$

The exact definition of Γ_{ij} and the inequalities that these parameter must satisfy to keep the complete positivity is can be found in Ref. [6] and we will not reproduce here. One important thing to have in mind is that the Γ_{ij} with $i \neq j$ are responsible by include decoherence effect while Γ_{ii} include the relaxation effect.

As in LBNE the matter potential has an important role, we will use the same analytical approximation scheme that was used in the Ref. [5]. In this scheme the matter parameters are given in terms of the usual effective parameters and this way, it is easy to apply this formalism to arrive the same expressions for survival and appearance probabilities as was given in Ref. [9] to the vacuum.

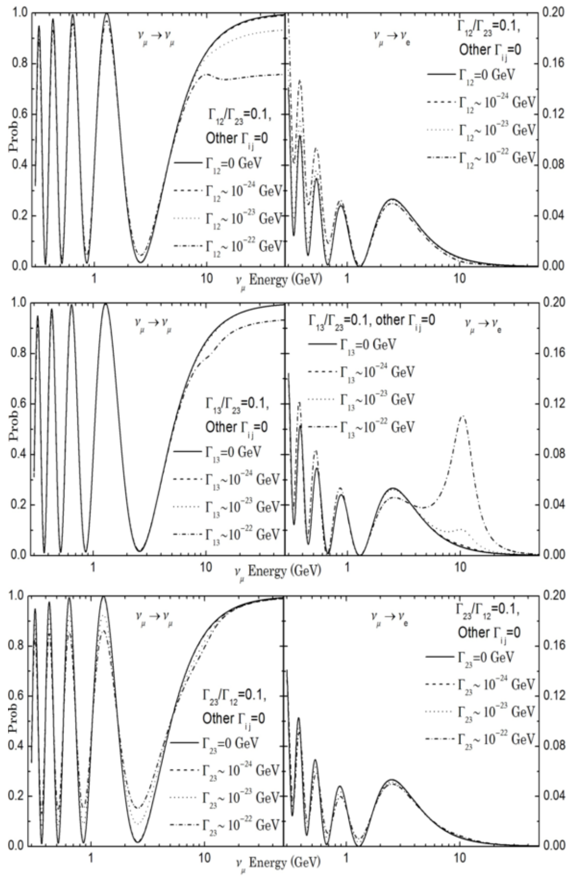

Figure 1: Survival and appearance probabilities to decoherence effects in LBNE.

In this situation, we can write together the complete probabilities for appearance and survival consiredering this muon source as

$$\begin{aligned} P_{\nu_\alpha \to \nu_{\alpha'}} =& \frac{1}{3} + \frac{1}{2}(|U_{\alpha 1}|^2 - |U_{\alpha 1}|^2)(|U_{\alpha' 1}|^2 - |U_{\alpha' 1}|^2) \\ & \times e^{-i\Gamma_{33} x} + \frac{1}{6} e^{-i\Gamma_{88} x} \times \\ & \sum_k (|U_{\alpha k}|^2 - 3|U_{\alpha 3}|^2)(|U_{\alpha' k}|^2 - 3|U_{\alpha' 3}|^2) \\ & + 2\sum_{j>k} Re(U_{\alpha' j} U^*_{\alpha j} U_{\alpha k} U^*_{\alpha' k}) e^{-i\Gamma_{jk} x} \cos \Delta_{jk} x \\ & + 2\sum_{j>k} Im(U_{\alpha' j} U^*_{\alpha j} U_{\alpha k} U^*_{\alpha' k}) e^{-i\Gamma_{jk} x} \sin \Delta_{jk} x \,, \end{aligned} \qquad (7)$$

where $\Delta_{jk} = \Delta m^2_{jk}/2E$ to $j > k$ and Γ_{jk} are given in Eq. (6). The $U_{\alpha i}$ are expression that can be obtained using the map results given in Ref. [5].

So, considering the LBNE, the distance between the source and the detector is 1300 km and to oscillation parameters we have used the following values: $\Delta m^2_{12} =$

$8{\times}10^{-23}$ GeV, $\Delta m^2_{31} = 2.5{\times}10^{-23}$ GeV, $\theta_{23} = 0.74$, $\theta_{12} = 0.58$, $\theta_{13} = 0.14$, $\delta = 0$ and the usual Earth density [3]. For a specific Γ_{ji} that we are interested, we vary its value about three different values as we can see in the figures 1 and 2. All of plots were made considering normal hierarchy.

In particular, the Fig. 2 shows the relaxation effects. They allow a bigger appearance neutrinos than the standard pattern to all of energy bins. This happens because the relation effects change the constant terms in the probabilities and they are responsible for becoming the probabilities a perfect mixing of the state, i. e., in the rate $1/3 : 1/3 : 1/3$. This rate is to when the propagation achieves its asymptotic limit $x \to \infty$. However, because they eliminate the constant terms in the probabilities, the maximum and minimum values of the probabilities change as well.

The decoherence effects, Γ_{21}, Γ_{31}, Γ_{32}, are represented in the Fig. 1. On the survival plots, we can see that the decoherence effect from Γ_{32} will be most effective than Γ_{21}, Γ_{31}, and this is expected because the main oscillation term comes from the usual parameters that describe transitions between the families ν_μ and ν_τ. However, from energy above of $E = 10$ Gev the behavior due to Γ_{21}, Γ_{31} parameters can change the probabilities in an exotic way because on the resonance region, the behavior depend on the ν_e parameters.

The appearance probabilities, we have the most interesting behavior due to the dissipative effects. Essentially, for understanding the strange behavior that was brought by Γ_{21} and Γ_{32} in the appearance probability, we need to keep in mind that decoherence effect acts in the decoupling of the oscillation between the families that are related by these parameters. So, in the Fig. 1 we can see that before $E = 2$ GeV Γ_{21} increases the appearance probability, while after $E = 2$ Gev Γ_{21} decreases it. Still in the Fig. 1, the Γ_{32} always decreases the maximum probability, but it increases all the minimum.

Γ_{31} is the most intriguing decoherence parameter because it acts under the effective potential mass terms. So, around of 4 Gev and before, its behavior is similar of the other decorence terms, except that Γ_{31} brings the little phase that is caused if the decoherence value is high. This happens because it eliminates the oscillation where the effective potential is most effective leading the oscillation for a vacuum regime.

The other interesting thing is a new peak that occurs around of 10 GeV that can be completely explained by means of the appearance probability in two families, where it is clear that the diference between constant and the amplitude term at the ressonace region results in this peak.

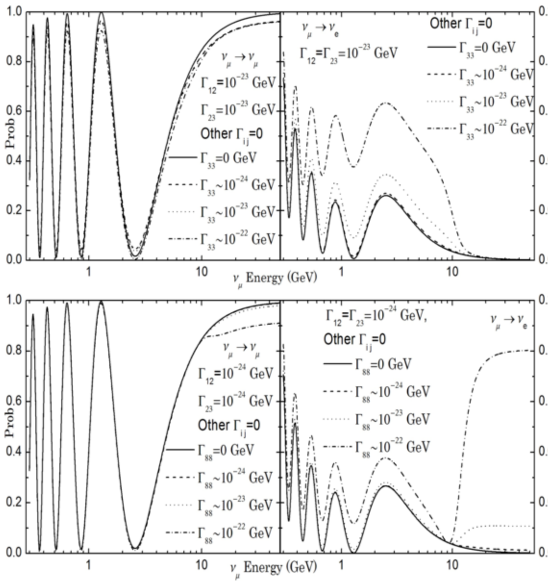

Figure2: Survival and appearance probabilities to relaxation parameters in LBNE.

3. Comments and Conclusion

We investigated dissipative effects in neutrinos oscillations concerning on the proposed LBNE set-up. We find that nontrivial effects can be observed at LBNE. Particularly interesting effects are expected in the “resonance region”, which is just outside the energy range of LBNE neutrinos. However, a considerable neutrino appearance is hoped in the end of spectrum that LBNE surely will have access. This will put a limit on Γ_{31} parameter.

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