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Prospects for reconstruction of leptonic unitarity quadrangle and neutrino oscillation experiments

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Abstract

After the observation of non-zero θ_{13} the goal has shifted to observe CP violation in the leptonic sector. Neutrino oscillation experiments can, directly, probe the Dirac CP phases. Alternatively, one can measure CP violation in the leptonic sector using Leptonic Unitarity Quadrangle (LUQ). The existence of Standard Model (SM) gauge singlets – sterile neutrinos – will provide additional sources of CP violation. We investigate the connection between neutrino survival probability and rephasing invariants of the 4×4 neutrino mixing matrix. In general, LUQ contain eight geometrical parameters out of which five are independent. We obtain CP asymmetry ($P_{\nu_f \to \nu_{f'}} - P_{\bar{\nu}_f \to \bar{\nu}_{f'}}$) in terms of these independent parameters of the LUQ and search for the possibilities of extracting information on these independent geometrical parameters in short baseline (SBL) and long baseline (LBL) experiments, thus, looking for constructing LUQ and possible measurement of CP violation. We find that it is not possible to construct LUQ using data from LBL experiments because CP asymmetry is sensitive to only three of the five independent parameters of LUQ. However, for SBL experiments, CP asymmetry is found to be sensitive to all five independent parameters making it possible to construct LUQ and measure CP violation.

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1. Introduction

The observation of non-zero θ_{13} [1–3] has, conclusively, established three types of oscillations and provides an opportunity for possible measurement of i) CP violation in the leptonic sector, and ii) to determine neutrino mass hierarchy. CP violation is, essentially, a three flavor effect [4] and is attributed to the non-trivial phases of the neutrino mixing matrix. In general, for three generation case, the neutrino mixing matrix contain three phases, one Dirac-type CP violating phase and two Majorana-type CP violating phases. However, only Dirac phase manifests itself in the neutrino oscillation experiments. Looking at the current and future neutrino facilities, which are either at planning or data acquisition stage, the measurement of CP violation is not beyond realization [5,6]. The current experimental data on neutrino masses and mixings can be explained within the paradigm of three active neutrino isodoublets. However, reconciliation with the short baseline (SBL) anomalies such as LSND, MiniBooNE and Gallium [7–12] requires the introduction of Standard Model (SM) gauge singlet(s)-sterile neutrino(s) because they involve the mass-squared difference, $\Delta m^2_{\text{SBL}} \gg \Delta m^2_{\text{Atm}} \gg \Delta m^2_{\text{Solar}}$. The possible existence of Standard Model (SM) gauge singlet fermion(s) is an attractive extension to our quest to understand fundamental physics including origin of non-zero neutrino masses and dark matter puzzle. In presence of sterile neutrinos, the standard three neutrino picture must be enlarged to accommodate the more mass eigenstates having non-zero mixing with the standard three active flavors. Also, there will be additional sources of CP violation in presence of these SM gauge singlets. So, it is important to study the prospects of detecting these additional sources of CP violation. In general, CP violation can be studied in two ways. One way is to directly measure CP violating phase in the neutrino oscillation experiments [5,6] and second is to construct the leptonic unitarity triangle (LUT)/quadrangle (LUQ) [13–15]. In the present work, we have followed the second approach. In four neutrino mixing models, CP violation is, generally, expected to be violated and is attributed to the nontrivial complex phases in 4×4 neutrino mixing matrix. Neutrino oscillation experiments play crucial role to study Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix and to, directly, measure CP violation, $P_{\nu_f \to \nu_{f'}} - P_{\bar{\nu}_f \to \bar{\nu}_{f'}} \neq 0$, in the leptonic sector. Alternatively, in order to measure CP violation, in a rephasing invariant manner using Leptonic Unitarity Quadrangle (LUQ), one has to construct rephase invariants from 4×4 neutrino mixing matrix V given by $J^{ij}_{ff'} \equiv \Im\left(V_{fi} V_{f'j} V^*_{fj} V^*_{f'i}\right)$ [16], where $(i, j) = 0, 1, 2, 3$ and $(f, f') = s, e, \mu, \tau$. In Sec. 2, we present the connection between neutrino survival probability and rephasing invariants of the 4×4 neutrino mixing matrix. In general, LUQ contain eight geometric parameters, out of which five parameters are independent. In Sec. 3, we present CP asymmetry, $P_{\nu_f \to \nu_{f'}} - P_{\bar{\nu}_f \to \bar{\nu}_{f'}}$, in terms of these independent parameters of the LUQ and search for the possibilities of extracting information on these independent geometrical parameters in short baseline (SBL) and long baseline (LBL) experiments, thus, looking for constructing LUQ and possible measurement of CP violation. In Sec. 4, we draw our conclusions.

2. Connecting leptonic unitarity quadrangle to mixing matrix

In four neutrino mixing, the flavor (ν_f, $f = s, e, \mu, \tau$) and mass eigenstates (ν_j, $j = 0, 1, 2, 3$) are connected through (4×4) unitary matrix V as