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CP violation in neutrino mass matrix

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Abstract

We constructed rephasing invariant measures of CP violation with elements of the neutrino mass matrix, in the basis in which the charged lepton mass matrix is diagonal. We discuss some examples of neutrino mass matrices with texture zeroes, where the present approach is applicable and demonstrate how it simplifies an analysis of CP violation. We applied our approach to study CP violation in all the phenomenologically acceptable 3-generation two-zero texture neutrino mass matrices and shown that in any of these cases there is only one CP phase which contributes to the neutrino oscillation experiment and there are no Majorana phases.

1. Introduction

In the Standard Model there is only one source of CP violation, which is in the charged–current mixing matrix in the quark sector. The charged–current mixing matrix in the quark sector contains one CP phase, which has been observed. It is not possible to identify the position of the CP phase, since it is possible to make any phase transformations to the quarks. However, it is possible to define a rephasing invariant quantity as product of elements of the mixing matrix that remains invariant under any rephasing of the quarks [1,2]. This is known as Jarlskog invariant.

In the leptonic sector, standard model does not allow any CP violation. If one considers extensions of the Standard Model to accommodate the observed neutrino masses, then there can be several CP phases [3–6]. In the simplest scenario of three generations, there could be one CP phase in the mixing matrix in the leptonic sector, similar to the quark sector. In addition, if neutrinos are Majorana particles they can have two more Majorana CP phases [4]. In this case

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it is possible to work in a parametrization, in which all the three CP phases could be in the charged–current mixing matrix in the leptonic sector. One of these CP phase will contribute to the neutrino oscillation experiments, while the other two will contribute to lepton number violating process like neutrinoless double beta decay. A natural explanation for the smallness of the neutrino masses comes from the see-saw mechanism [7]. The origin of small neutrino mass then relates to a large lepton number violating scale. It is quite natural that this lepton number violation at the high scale would also explain the baryon asymmetry of the universe through leptogenesis [8,9]. This connection between the neutrino mass and leptogenesis makes the question of CP violation in the leptonic sector more interesting [5,6].

The CP phases in the leptonic sector has been studied and rephasing invariants for both lepton number conserving as well as lepton number violating processes have been constructed [3]. In this article we try to study this question only in terms of neutrino masses. Since neutrinos are produced only through weak interactions, it is possible to work in the weak interaction basis, in which the charged lepton mass matrix is diagonal. The neutrino mass matrix in this basis will then contain all the information about CP violation. We try to find rephasing invariant combinations of the neutrino mass elements, so that with those invariants some general comments can be made about CP violation in the model without deriving the structure of the charged–current mixing matrix.

2. CP violation in the quark sector

We briefly review the rephasing invariants in terms of the mixing matrices and then show how the same results can be obtained from the mass matrix without taking the trouble of diagonalizing them in the leptonic sector. Consider first the quark sector, where the up and the down quark mass matrices are diagonalized by the bi-unitary transformations. We write the corresponding unitary matrices that relates the left-handed and right-handed physical (with definite masses) up and down quarks fields to their weak (diagonal charged current) basis as: U_L, D_L, U_R and D_R. Then the charged current interactions in terms of the physical fields will contain the Kobayashi–Cabibbo–Maskawa mixing matrix

$$V = D_L^\dagger U_L.$$

Since the right-handed fields are singlets under the standard model interactions, they do not enter in the charged current interactions. In any physical processes, only this CKM mixing matrix would appear and hence the matrices U_R and D_R becomes redundant. So, the up and down quark masses have much more freedom and the physical observables that can determine the $V_{\alpha i}$ cannot infer about the up and down quark masses uniquely.

For the CP violation, one needs to further consider the rephasing of the left-handed fields. Any phase transformation to the up and down quarks will also transform the CKM matrix

$$V_{\alpha i} \to e^{-i(d_\alpha - u_i)}.$$

However, if there is any CP phase in the CKM matrix, which cannot be removed by any phase transformations of the up and the down quarks, should be present in the Jarlskog invariant [1,2]

$$J_{\alpha i \beta j} = \mathrm{Im}\big[V_{\alpha i} V_{\beta j} V^*_{\alpha j} V^*_{\beta i}\big]. \tag{1}$$

Thus if the Jarlskog invariant is non-vanishing, that would imply CP violation in the quark mixing. It is apparent from the definition that any phase transformations to the up and down quarks