Unitarity triangles and geometrical description of *CP* violation with Majorana neutrinos

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We generalize the geometrical description of CP violation in the standard model in terms of a unitarity triangle. For three left-handed Majorana neutrinos CP violation in the lepton sector is determined by three unitarity triangles. With three additional right-handed neutrinos 15 quadrangles are required to characterize CP violation. We show the relation of the unitarity polygons with physical observables.

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I. INTRODUCTION

The recent SuperKamiokande data [1] on atmospheric neutrinos provide evidence for neutrino oscillations, thus suggesting that neutrinos have non-vanishing masses. The simplest way of understanding the smallness of these masses is through the seesaw mechanism [2] which naturally leads to Majorana neutrinos.

In this article we provide a geometrical interpretation of CP violation with Majorana neutrinos. In the quark sector of the three-generation standard model (SM) it is well known that CP violation can be described by six unitarity triangles [3]. They are obtained from orthogonality of the rows and columns of the Cabibbo-Kobayashi-Maskawa (CKM) matrix V [4], and are all equivalent. Under a rephasing transformation of the quark fields, these unitarity triangles rotate and therefore their orientation has no physical meaning. However, their area does have physical meaning and in fact all six triangles have the same area which is proportional to the rephasing invariant CP violating quantity $|\mathrm{Im}\, V_{ij} V_{kj}^* V_{kl} V_{il}^*|$ [5]. It is natural to ask how this geometrical analysis can be extended to the leptonic sector, when Majorana neutrinos are present. In this article we will address this question, considering first the cases of three and four left-handed Majorana neutrinos and then the case of three left-handed and an arbitrary number of right-handed neutrinos. We will interpretate the well-known features of CP violation for Majorana neutrinos in terms of geometrical properties of polygons.

II. GEOMETRICAL INTERPRETATION FOR THREE LEFT-HANDED NEUTRINOS

In the SM extension with Majorana neutrino masses, the mass terms of the leptonic Lagrangian, in the weak eigenstate basis, can be written as

$$-\mathcal{L}_{\mathrm{mass}} = \overline{l_L^0} M_l l_R^0 + \frac{1}{2} \overline{\nu_L^0} M_L (\nu_L^0)^c + \mathrm{H.c.}, \tag{1}$$

where l_L^0, l_R^0 and ν_L^0 are three-dimensional vectors in flavor space, M_l and M_L are 3×3 complex matrices and $(\nu_L^0)^c = C(\overline{\nu_L^0})^T$. Here M_L can be taken as symmetric without loss of generality. The mass term for the neutrinos can be generated extending the scalar sector with a Higgs triplet or can be the result of a seesaw mechanism [2]. The charged current term in this basis is

$$-\mathcal{L}_{\mathrm{CC}} = \frac{g}{\sqrt{2}} \overline{\nu_L^0} \gamma^\mu l_L^0 W_\mu^\dagger + \mathrm{H.c.} \tag{2}$$

The leptonic mass matrices M_l, M_L are diagonalized through the transformations $l_L^0 = U_L^l l_L$, $\nu_L^0 = U_L^\nu \nu_L$, $l_R^0 = U_R^l l_R$, with $U_L^{l,\nu}$, U_R^l 3×3 unitary matrices, so that $U_L^{l\dagger} M_l U_R^l = D_l$, $U_L^{\nu\dagger} M_L U_L^{\nu *} = D_L$ where D_l, D_L are the diagonal mass matrices. One can then write, in the mass eigenstate basis,

$$-\mathcal{L}_{\mathrm{mass}} = \overline{l_L} D_l l_R + \frac{1}{2} \overline{\nu_L} D_L (\nu_L)^c + \mathrm{H.c.},$$

$$-\mathcal{L}_{\mathrm{CC}} = \frac{g}{\sqrt{2}} \overline{\nu_L} \gamma^\mu U l_L W_\mu^\dagger + \mathrm{H.c.} \tag{3}$$

The mixing matrix $U = U_L^{\nu\dagger} U_L^l$ is the analogue of the CKM matrix in the quark sector, and can be parametrized with 3 mixing angles and 6 phases. The phase of the charged lepton mass eigenstates is arbitrary, and we can use this freedom to eliminate three of these phases. However, the phase of the neutrino mass eigenstates cannot be changed, since this transformation does not leave invariant the neutrino mass matrix in Eq. (3). Hence the mixing matrix U has in general three independent, CP violating physical phases instead of one. Two of these phases are ''Majorana phases'' that could be removed if rephasing of the neutrino fields was allowed. The other phase is the analogous to the CKM phase which cannot be removed even for Dirac neutrinos, a ''Dirac phase.''

The mixing matrix can be parametrized in general as a diagonal matrix of phases multiplied by a 3×3 unitary matrix in the standard parametrization [6]

$$U=\begin{pmatrix}1&0&0\\0&e^{i\alpha_2}&0\\0&0&e^{i\alpha_3}\end{pmatrix}\begin{pmatrix}c_{12}c_{13}&s_{12}c_{13}&s_{13}e^{-i\delta}\\-s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta}&c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta}&s_{23}c_{13}\\s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta}&-c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta}&c_{23}c_{13}\end{pmatrix}. \quad (4)$$

In this parametrization, δ is the Dirac phase and α_2, α_3 are the Majorana phases. CP is conserved if $\delta=0 \mod \pi$ and $\alpha_2=0$, $\alpha_3=0 \mod \pi/2$ (from now on we will write for simplicity $\delta=0$, $\alpha_2=0$, $\alpha_3=0$). Note that Majorana phases of $\pm\pi/2$ do not imply CP violation but indicate different CP parities of the neutrino mass eigenstates [7].

The only rephasing transformations allowed are $l_{Lj,Rj} \to e^{i\lambda_j} l_{Lj,Rj}$. Under these transformations, the matrix elements of U transform as $U_{ij} \to e^{i\lambda_j} U_{ij}$. Hence the minimal rephasing invariant terms are the products $U_{ij}U_{kj}^*$, and the minimal CP violating quantities their imaginary parts $\mathrm{Im}\, U_{ij}U_{kj}^*$.[1]

One can define triangles analogous to those depicted in the quark sector by multiplying two columns of U, e.g., $U_{11}U_{13}^*+U_{21}U_{23}^*+U_{31}U_{33}^*=0$. Under rephasing transformations, these triangles rotate in the complex plane, $U_{ij}U_{ik}^* \to e^{i(\lambda_j-\lambda_k)}\, U_{ij}U_{ik}^*$, so their orientation has no physical meaning. They share a common area $A=1/2\, |\mathrm{Im}\, U_{ij}U_{kj}^*U_{kl}U_{il}^*|$. We will call these triangles ''Dirac triangles.'' The vanishing of their area implies $\mathcal{J}_U \equiv |\mathrm{Im}\, U_{ij}U_{kj}^*U_{kl}U_{il}^*|=0$, but does not imply that the minimal CP violating quantities $\mathrm{Im}\, U_{ij}U_{kj}^*$ are zero, and CP can still be violated. In terms of phases, $\mathcal{J}_U=0$ implies that the Dirac phase vanishes [$\delta=0$ in the parametrization in Eq. (4)] but the Majorana phases can still violate CP. Thus these triangles provide a necessary but not sufficient condition for CP conservation and are not enough to completely describe CP violation.

One can also define three ''Majorana triangles'' multiplying two rows of U (see Fig. 1):

$$T_{12}\equiv U_{11}U_{21}^*+U_{12}U_{22}^*+U_{13}U_{23}^*=0,$$

$$T_{13}\equiv U_{11}U_{31}^*+U_{12}U_{32}^*+U_{13}U_{33}^*=0,$$

$$T_{23}\equiv U_{21}U_{31}^*+U_{22}U_{32}^*+U_{23}U_{33}^*=0. \quad (5)$$

Under a change of phase these triangles do not rotate in the complex plane, since all their terms are rephasing invariant. Thus their orientation is physically meaningful. These Majorana triangles provide the necessary and sufficient conditions for CP conservation:

(1) Vanishing of their common area $A=\mathcal{J}_U/2$.

(2) Orientation of all Majorana triangles along the direction of the real or imaginary axes.

The first condition implies that the three triangles collapse into lines in the complex plane and the Dirac phase vanishes. Condition (2) implies that the Majorana phases do not violate CP. If the three collapsed triangles are on the x axis, one has $\mathrm{Im}\, U_{ij}U_{kj}^*=0\ \forall i,j,k$ and CP is obviously conserved. If one of these triangles, T_{ik}, is parallel to the y axis, that means that the mass eigenstates ν_i and ν_k have opposite CP parities, but there is not CP violation. Multiplying the i or the k row by $\pm i$ we can rotate the triangle to the x axis, making the mass of the corresponding eigenstate negative. Hence the three Majorana triangles provide a complete description of CP violation. Each one of their sides, if not parallel to one of the axes, is itself a signal of CP violation, contrarily to the Dirac case where only a nonzero area signals CP violation.

One may wonder whether the three conditions (2) are independent, i.e., whether the orientations of the three triangles are related. If at least one column of U, e.g., the first column, has nonzero elements, one has

$$\arg U_{11}U_{31}^*=\arg U_{11}U_{21}^*+\arg U_{21}U_{31}^* \mod 2\pi. \quad (6)$$

This is true independently of the area A, but in the case of vanishing areas, Eq. (6) implies that the angles between the triangles and the real axis are related, and only two triangles are needed, for instance T_{12} and T_{13}. Requiring that these two triangles are on the x or y axis eliminates the two Majorana phases.

To describe CP violation in the most general cases, the three triangles are needed. In order to see that this is the case, let us consider the mixing matrix

$$U=\begin{pmatrix}1&0&0\\0&1/\sqrt{2}&1/\sqrt{2}\\0&e^{i\alpha}/\sqrt{2}&-e^{i\alpha}/\sqrt{2}\end{pmatrix}. \quad (7)$$

For this particular matrix, T_{12} and T_{13} are trivial, and CP is violated unless $\alpha=0 \mod \pi/2$; i.e., T_{23} is parallel to one of the axes. Analogous mixing matrices can be written to show that T_{12} and T_{13} are necessary in general.

To conclude this section, let us discuss two interesting special cases. If one neutrino is massless, e.g., $m_{\nu_1}=0$, the phase of ν_1 can be changed, leaving $\mathcal{L}_{\mathrm{mass}}$ invariant. The

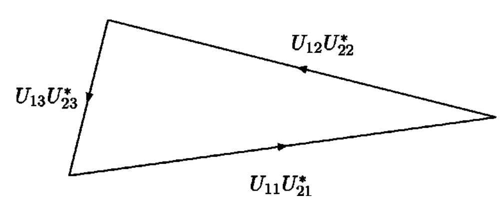

FIG. 1. Majorana unitarity triangle T_{12}. Its orientation is fixed by the Majorana phases and it cannot be rotated in the complex plane.

[1]Strictly speaking, $\mathrm{Im}\, U_{ij}U_{kj}^*$ are not CP violating if $\mathrm{Re}\, U_{ij}U_{kj}^*=0$ (see Sec. IV).

orientation of the triangles T_{12} and T_{13} has no physical meaning, and all CP violation can be summarized in T_{23}. In this case we have only the Dirac phase (δ) and one Majorana phase (α_3). Requiring that the area of T_{23} be zero eliminates δ, and requiring that T_{23} be parallel to the x or y axis eliminates α_3. The cases $m_{\nu_2}=0$ and $m_{\nu_3}=0$ are similar.

In the case that there is one and only one zero in U, e.g., U_{31}, the three triangles have null area and the Dirac phase is zero. The orientations of the three triangles are related and only two of them are necessary to describe CP violation. If there are two zeros in the mixing matrix, U is analogous to the matrix in Eq. (7) with at most one Majorana phase, and only one triangle is nontrivial.

III. GENERALIZATIONS

A. Four left-handed neutrinos

Before considering the inclusion of right-handed neutrinos it is convenient to analyze the simpler case of four left-handed neutrinos. The CKM matrix in this case is a 4×4 matrix, with three Dirac phases and three Majorana phases. The unitarity relations between its rows can be represented in the complex plane as six Majorana quadrangles. For example, the orthogonality condition between the first and second rows can be represented as the quadrangle

$$Q_{12}\equiv U_{11}U_{21}^{*}+U_{12}U_{22}^{*}+U_{13}U_{23}^{*}+U_{14}U_{24}^{*}=0. \qquad (8)$$

Its area is[2]

$$A_{12}=\frac{1}{4}\{|\mathrm{Im}\,U_{11}U_{21}^{*}U_{22}U_{12}^{*}|+|\mathrm{Im}\,U_{12}U_{22}^{*}U_{23}U_{13}^{*}| + |\mathrm{Im}\,U_{13}U_{23}^{*}U_{24}U_{14}^{*}|+|\mathrm{Im}\,U_{14}U_{24}^{*}U_{21}U_{11}^{*}|\}. \qquad (9)$$

If $A_{12}=0$, the four imaginary products are zero. The condition for the vanishing of the three Dirac phases is that the areas of three independent convex quadrangles (for instance, Q_{12}, Q_{23}, Q_{34} or Q_{12}, Q_{13}, Q_{23}) be zero [8]. When this condition is satisfied, the areas of all the quadrangles are zero. To describe CP violation with all generality the six quadrangles Q_{12}, Q_{13}, Q_{14}, Q_{23}, Q_{24}, Q_{34} are necessary, since there are special cases when all quadrangles but one are trivial. CP is conserved if, and only if, these six convex quadrangles have null area and are orientated in the direction of one of the axes. However, if at least one column of U has all elements non-vanishing, e.g., the first column,

$$\arg U_{11}U_{31}^{*}=\arg U_{11}U_{21}^{*}+\arg U_{21}U_{31}^{*} \mod 2\pi,$$

$$\arg U_{21}U_{41}^{*}=\arg U_{21}U_{31}^{*}+\arg U_{31}U_{41}^{*} \mod 2\pi,$$

$$\arg U_{11}U_{41}^{*}=\arg U_{11}U_{21}^{*}+\arg U_{21}U_{31}^{*} +\arg U_{31}U_{41}^{*} \mod 2\pi, \qquad (10)$$

and the three quadrangles Q_{12}, Q_{23}, and Q_{34} completely characterize CP violation.

[2]For simplicity we assume that Q_{12} when drawn in the order of Eq. (8) is convex. In other case, its sides must be reordered, obtaining an expression similar to Eq. (9). The results are unchanged.

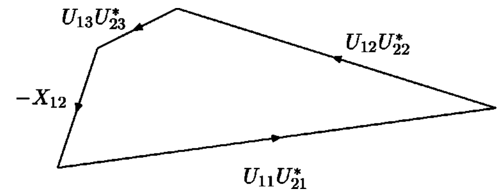

FIG. 2. Majorana unitarity quadrangle Q_{12} for an arbitrary number of right-handed neutrinos n_R. Its orientation is fixed by the Majorana phases and it cannot be rotated in the complex plane.

B. Three left-handed and n_R right-handed neutrinos

The case of 3 left-handed and n_R right-handed neutrinos is similar to the extension of the SM with n_R up-type quark singlets, with some differences due to the Majorana character of the neutrinos. The CKM mixing matrix U is a $(3+n_R)\times 3$ submatrix of a $(3+n_R)\times(3+n_R)$ unitary matrix, with $2n_R+1$ Dirac phases and n_R+2 Majorana phases. In addition, the neutral current Lagrangian contains nondiagonal terms,

$$-\mathcal{L}_{\mathrm{NC}}=\frac{g}{2c_W}\overline{\nu_L}\gamma^{\mu}X\nu_L Z_{\mu}+\mathrm{H.c.}, \qquad (11)$$

where X is a $(3+n_R)\times(3+n_R)$ Hermitian matrix with complex nondiagonal elements. Note that ν_L is a linear combination of weak eigenstates ν_L^0, $(\nu_R^0)^c$ with different isospin. However, the flavor-changing neutral (FCN) couplings do not contain additional CP violating phases. For any number of right-handed neutrinos, n_R, the unitarity relations between rows of U can be represented as convex Majorana quadrangles in the complex plane [9]. For example, the orthogonality condition between the first and second rows reads

$$Q_{12}\equiv U_{11}U_{21}^{*}+U_{12}U_{22}^{*}+U_{13}U_{23}^{*}=X_{12}, \qquad (12)$$

with X_{12} the FCN coupling between the neutrino mass eigenstates ν_1 and ν_2 (see Fig. 2).

The geometrical interpretation is then very similar to the previous case. The condition for the vanishing of the $2n_R+1$ Dirac phases is that the area of $(n_R+2)(n_R+1)/2$ independent convex quadrangles is zero, for instance Q_{12}, $Q_{23}\dots Q_{n_R+2,n_R+3}$. In this case, the areas of the remaining quadrangles are also zero. The condition for the vanishing of the n_R+2 Majorana phases is that all the $(n_R+3)(n_R+2)/2$ quadrangles are parallel to the x or y axis. Hence, the complete description of CP violation with three left-handed and n_R right-handed neutrinos is achieved with $(n_R+3)(n_R+2)/2$ quadrangles. Note that in the limit where the heavy neutrinos decouple, $X_{ij}=\delta_{ij}$ for $i,j=1,2,3$, and the three

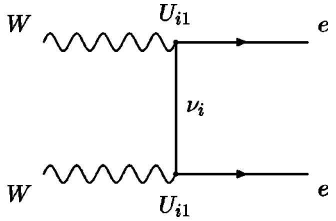

FIG. 3. Feynman diagram for neutrinoless double beta decay mediated by Majorana neutrinos.

quadrangles involving only the light neutrinos reduce to the three triangles described in the previous section. The other quadrangles are trivial.

IV. UNITARITY POLYGONS AND PHYSICAL OBSERVABLES

Relevant information on the unitarity polygons (and the CP violating phases) can be extracted from CP violating and CP conserving processes. The CP violating processes may be sensitive to the Majorana phases or may not. We will show examples of each case.

CP violation in neutrino oscillations is not sensitive to Majorana phases. The Dirac or Majorana character of the neutrinos is not revealed in this kind of experiments, and thus CP violation observables are proportional to imaginary quartets $\mathrm{Im}\, U_{ij} U_{kj}^* U_{kl} U_{il}^*$. Neutrino oscillations can only provide information on the areas of the unitarity polygons and the Dirac phases.

One important process to test the Majorana character of the neutrinos is neutrinoless double-beta decay. This process is mediated by the diagram in Fig. 3, where we can observe that the Majorana character of the neutrinos is essential.

The cross section of this process is

$$\sigma = C \sum_{i,j} m_{\nu_i} m_{\nu_j} (U_{i1} U_{j1}^*)^2, \tag{13}$$

where the rephasing invariance is explicit. C is a factor independent of the mixing angles. There are terms proportional to $|U_{i1}|^4$ and also terms proportional to the first sides of the triangles (or quadrangles), the sides involving the couplings of the neutrinos to the electron. The measurement of the neutrinoless double beta decay rate then serves to constrain the CP violating parameters.

The decay of heavy Majorana neutrinos has been proposed as a source of CP violation for baryogenesis [10]. Here for definiteness we will consider the CP asymmetry in the decay of a heavy neutrino, $\nu_4 \to W^+ e$. The tree-level and one-loop diagrams relevant for the CP asymmetry in this decay are shown in Fig. 4. Note that the Majorana character of the neutrinos plays an essential role in the second diagram. There are four more one-loop diagrams not taken into account. Two of them involve Z and photon exchange between the electron and the W. They have the same weak phase as the tree-level diagram and do not contribute to the CP asymmetry at lowest order. The other two involve Z exchange between the neutrino and the electron and W, respectively. If FCN couplings are neglected, they also have the same weak phase as the tree-level diagram.

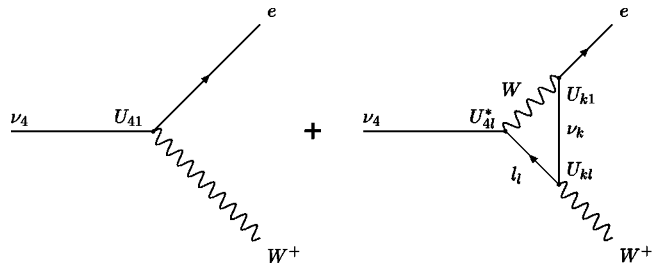

FIG. 4. Tree-level and one-loop contributions to the CP asymmetry in the decay of a heavy Majorana neutrino, $\nu_4 \to W^+ e$.

The difference $\Gamma(\nu_4 \to W^+ e) - \overline{\Gamma}(\nu_4 \to W^- e^+)$ is a CP violating observable. Extracting the dependence on the mixing angles it can be written as

$$\Gamma - \overline{\Gamma} = \sum_{k,l} f_{kl} \,\mathrm{Im}\,(U_{41} U_{k1}^*)\,(U_{4l} U_{kl}^*), \tag{14}$$

with f_{kl} form factors independent of mixing angles. To understand this formula we observe in Fig. 4 that the mixing angle factors of the tree-level and one-loop contributions, U_{41} and $U_{kl} U_{4l}^* U_{k1}$ respectively, transform in the same way under rephasing of the charged lepton fields (as they must), but not under rephasing of the neutrino mass eigenstates (as they should in the case of Dirac neutrinos). If the two mixing angle factors transformed in the same way under rephasing of the neutrino mass eigenstates, we would have a dependence $\Gamma - \overline{\Gamma} \propto \mathrm{Im}\, U_{41} U_{k1}^* U_{kl} U_{4l}^*$ or similar, and the asymmetry would not be sensitive to the Majorana phases. The diagrams involving Z exchange between the neutrino and e, W give an additional contribution of this type.

The CP asymmetry in Eq. (14) is written as a linear combination of imaginary parts of products of the sides $1,l$ of the quadrangle Q_{4k}, summing over k and l. The terms with $l=1$ contain $\mathrm{Im}\,(U_{41} U_{k1}^*)^2 = 2\,\mathrm{Re}\,(U_{41} U_{k1})\,\mathrm{Im}\,(U_{41} U_{k1})$. We see that a side of Q_{4k} does not contribute to the CP asymmetry if it is parallel to one of the axes, although it may contribute in the terms of mixing with other sides if the Dirac phases are nonzero, i.e., if other sides of the same quadrangle are CP violating.

Finally we will show the relation between the unitarity triangles and the weak-basis invariants. The lowest order weak-basis invariant for three left-handed Majorana neutrinos is [11]

$$I = \mathrm{Im\,tr}\, M_l M_l^\dagger M_L M_l^* M_l^T M_L^* M_L M_L^*$$
$$= \sum_{i,j,k,l} m_j^2 m_l^2 m_{\nu_i}^3 m_{\nu_k} \mathrm{Im}\,(U_{ij} U_{kj}^*)\,(U_{il} U_{kl}^*), \tag{15}$$

with m_i the mass of the charged lepton i. In Eq. (15) rephasing invariance is explicit. The invariant is written as a sum of imaginary parts of products of two sides j,l of the same triangle T_{ik} weighted by mass factors. The terms with $j=l$ are proportional to $\mathrm{Im}\,(U_{ij} U_{kj}^*)^2 = 2\,\mathrm{Re}\,(U_{ij} U_{kj}^*)\,\mathrm{Im}\,(U_{ij} U_{kj}^*)$. We see that a side of T_{ik} parallel to the real or imaginary axis does not contribute to I. If the Dirac phase is also zero, the whole contribution of T_{ik} is zero. Thus, although the minimal CP violating quantities are $\mathrm{Im}\, U_{ij}U^{*}_{kj}$, they need to interfere with their real part or with other sides of unitarity triangles.

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[1] Y. Fukuda *et al.*, Phys. Rev. Lett. **82**, 2644 (1999).
[2] M. Gell-Mann, P. Ramond, and R. Slansky, in *Supergravity*, edited by P. van Nieuwenhuizen and D. Z. Freedman (North-Holland, Amsterdam, 1979); T. Yanagida, Prog. Theor. Phys. **64**, 1103 (1980); R. N. Mohapatra and G. Senjanović, Phys. Rev. Lett. **44**, 912 (1980).
[3] G. C. Branco and L. Lavoura, Phys. Lett. B **208**, 123 (1988); C. Jarlskog and R. Stora, *ibid.* **208**, 268 (1988); see also H. Fritzsch and Z.-Z. Xing, Prog. Part. Nucl. Phys. **45**, 1 (2000).
[4] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
[5] C. Jarlskog, Phys. Rev. Lett. **55**, 1039 (1985); I. Dunietz, O. W. Greenberg, and D.-D. Wu, *ibid.* **55**, 2935 (1985).
[6] L.-L. Chau and W. Keung, Phys. Rev. Lett. **53**, 1802 (1984).
[7] L. Wolfenstein, Phys. Lett. **107B**, 77 (1981).
[8] F. del Aguila and J. A. Aguilar-Saavedra, Phys. Lett. B **386**, 241 (1996).
[9] Y. Nir and D. J. Silverman, Phys. Rev. D **42**, 1477 (1990); G. C. Branco, T. Morozumi, P. A. Parada, and M. N. Rebelo, *ibid.* **48**, 1167 (1993); V. Barger, M. S. Berger, and R. J. Phillips, *ibid.* **52**, 1663 (1995); F. del Aguila, J. A. Aguilar-Saavedra, and G. C. Branco, Nucl. Phys. **B510**, 39 (1998); G. Barenboim, F. J. Botella, G. C. Branco, and O. Vives, Phys. Lett. B **422**, 277 (1998); P. H. Frampton, P. Q. Hung, and M. Sher, Phys. Rep. **330**, 263 (2000).
[10] W. Buchmüller and M. Plümacher, Phys. Lett. B **389**, 73 (1996); **431**, 354 (1998).
[11] G. C. Branco, L. Lavoura, and M. N. Rebelo, Phys. Lett. B **180**, 264 (1986); F. del Aguila and M. Zrałek, Nucl. Phys. **B447**, 211 (1995); F. del Aguila, J. A. Aguilar-Saavedra, and M. Zrałek, Comput. Phys. Commun. **100**, 231 (1997).