PHYSICAL REVIEW D VOLUME 49, NUMBER 7 1 APRIL 1994

Pure phase mass matrices

Paul M. Fishbane
Physics Department and Institute for Nuclear and Particle Physics, University of Virginia, Charlottesville, Virginia 22901

Peter Kaus
Physics Department, University of California, Riverside, California 92521

(Received 24 September 1993)

We study quark mass matrices whose matrix elements in a given quark sector differ only in their phases and we describe how such matrices can be compared with quark masses and family mixing.

PACS number(s): 12.15.Ff

I. INTRODUCTION

The pure-phase mass matrix [1,2] is a particularly interesting realization of a democratic mass matrix [3]. Although no known dynamical scheme generates this picture, the possibility that only a single Yukawa coupling strength appears in a given fermionic sector is sufficiently attractive to warrant a better understanding of its implications for phenomenology.

We refer to a pure phase mass matrix as one with elements

$$M_{ij}=e^{i\phi_{ij}} . \tag{1.1}$$

We shall explore the possibility that such matrices describe the quark masses in both the down and up sectors. The two sectors will, in general, have different phases, and each of the two matrices has a different normalization that we leave unspecified for the moment. We can always choose the phase of states so that $\phi_{11}=0=\phi_{22}=\phi_{33}$, and we do so henceforth.

We take for masses at 1 GeV in the up sector, $m_1=5.1$ MeV, $m_2=1360$ MeV, and for illustration,[1] $m_3=3\times10^5$ MeV and, in the down sector, $m_1=8.9$ MeV, $m_2=145$ MeV, and $m_3=5700$ MeV. Let us define, $w_i\equiv m_i^2$. The normalization we choose will make the sum of the masses squared in both the down and up sectors equal to three. Thus the w's are given by dividing out the sum of the masses squared in each sector and multiplying by 3. We can then set w_3 equal to $3-w_1-w_2$. With this normalization, we have in the up sector $w_1=8.643\times10^{-10}$, $w_2=6.162\times10^{-5}$; for the down sector, $w_1=7.29\times10^{-6}$, $w_2=1.944\times10^{-3}$. It is also useful to work with the mass ratios w_1/w_3 and w_2/w_3. These are given, respectively, by 2.88×10^{-10} and 2.05×10^{-5} in the up sector and 2.43×10^{-6} and 0.64×10^{-3} in the down sector. If $w_2/w_3=\epsilon_d^2$ and ϵ_u^2 in the down and up sectors, then $\epsilon_d=0.0255$ and $\epsilon_u=0.0045$. In each case w_1/w_3 is $O(\epsilon^4)$ (or smaller). We shall henceforth think of w_2 as $O(\epsilon^2)$ and w_1 as $O(\epsilon^4)$. The small quantity ϵ will provide a convenient expansion scheme for our discussion.

[1]For a QCD scale of 150 MeV, a top quark mass of 3×10^5 MeV at 1 GeV corresponds to a physical mass of some 140 GeV.

We have several different aims in this note. We want to show in what way the hierarchy inherent in masses and in the Cabibbo-Kobayashi-Maskawa (CKM) matrix reveals itself in the pure-phase mass matrix. We want to describe the full parameter space that is consistent with the current values of the CKM matrix elements. In this way we can provide a framework for any future dynamical model that leads to a pure-phase mass matrix. Moreover, we can prepare to see whether improved experimental data on the values of the CKM matrix elements can be accommodated in a pure-phase mass matrix. Finally, the question of whether a pure-phase mass matrix can be constructed with a reduced parameter set, for example, whether it is symmetric or reflects some type of texture, is a potentially interesting one. The groundwork we lay in this note will allow us to explore such questions in future work.

II. PARAMETRIZATION

The pure-phase mass matrix in Eq. (1.1) is not necessarily Hermitian; it is simpler for our purposes to work not with M as in Eq. (1.1) but with the Hermitian matrix $H\equiv\frac{1}{3}MM^\dagger$. The diagonal elements of this matrix each equal three, and the off-diagonal elements are given by

$$3H_{21}=e^{i\phi_{21}}+e^{-i\phi_{12}}+e^{-i(\phi_{13}-\phi_{23})} , \tag{2.1a}$$

$$3H_{31}=e^{i\phi_{31}}+e^{-i(\phi_{12}-\phi_{32})}+e^{-i\phi_{13}} , \tag{2.1b}$$

$$3H_{32}=e^{-i(\phi_{21}-\phi_{31})}+e^{i\phi_{32}}+e^{-i\phi_{23}} . \tag{2.1c}$$

The exact eigenvalues of the matrix H are given by

$$w_1=\frac{2\sqrt{3}}{9}\sqrt{2c_1+9}\times\cos\left\{\frac{1}{3}\arcsin\left[\frac{3\sqrt{3}(4c_1+c_2)}{2\sqrt{(2c_1+9)^3}}\right]-\frac{5\pi}{6}\right\}+1 , \tag{2.2a}$$

$$w_2=\frac{2\sqrt{3}}{9}\sqrt{2c_1+9}\times\cos\left\{\frac{1}{3}\arcsin\left[\frac{3\sqrt{3}(4c_1+c_2)}{2\sqrt{(2c_1+9)^3}}\right]+\frac{\pi}{2}\right\}+1 , \tag{2.2b}$$

$$w_3=\frac{2\sqrt{3}}{9}\sqrt{2c_1+9}\times\cos\left\{\frac{1}{3}\arcsin\left[\frac{3\sqrt{3}(4c_1+c_2)}{2\sqrt{(2c_1+9)^3}}\right]-\frac{\pi}{6}\right\}+1\ . \quad (2.2c)$$

In Eqs. (2.2), we use

$$c_1\equiv\cos\theta_1+\cos\theta_2+\cos\theta_3+\cos\theta_4+\cos(\theta_4-\theta_1)+\cos(\theta_4-\theta_3)+\cos(\theta_4+\theta_2-\theta_1)+\cos(\theta_4+\theta_2-\theta_3)+\cos(\theta_4+\theta_2-\theta_1-\theta_3)\ , \quad (2.3)$$

$$c_2\equiv2[3+\cos(\theta_3-\theta_2)+\cos(\theta_3-\theta_1)+\cos(\theta_2-\theta_1)+\cos(\theta_4+\theta_2)+\cos(\theta_4-\theta_1-\theta_3)+\cos(2\theta_4+\theta_2-\theta_1-\theta_3)]\ . \quad (2.4)$$

These quantities contain only four linear combinations of the six angles appearing in the mass matrix: namely,[2]

$$\theta_1\equiv\phi_{23}+\phi_{32}\ , \quad (2.5a)$$

$$\theta_2\equiv\phi_{13}+\phi_{31}\ , \quad (2.5b)$$

$$\theta_3\equiv\phi_{12}+\phi_{21}\ , \quad (2.5c)$$

$$\theta_4\equiv\phi_{12}-\phi_{13}+\phi_{23}\ . \quad (2.5d)$$

The three invariants of H are 3 [trace, $w_1+w_2+w_3$], $2(9-c_1)[w_1w_2+w_1w_3+w_2w_3]$, and c_2-2c_1[determinant, $w_1w_2w_3$].

The eigenvalues differ only by phase factors of 120°. When all phases vanish, we recover the primitive Nambu symmetry, in which $w_1=w_2=0$, while $w_3=3$. To the extent a perturbative expansion makes sense, with $w_3=$const, $w_2=O(\epsilon^2)$, and $w_1=O(\epsilon^4)$, the expression for the second order invariant shows that $9-c_1=O(\epsilon^2)$, while the expression for the determinant shows that c_2-2c_1 must be $O(\epsilon^6)$. The angles $\theta_1,\ldots,\theta_4$ are in turn each $O(\epsilon)$. Moreover, the masses can be developed as well-behaved (invertible) expansions in $9-c_1$ and c_2-2c_1, and in particular the leading behavior is

$$w_2=\frac{2(9-c_1)}{27}\ , \quad (2.6)$$

$$w_1=\frac{c_2-2c_1}{6(9-c_1)}\ . \quad (2.7)$$

Following Branco, Silva-Marcos, and Rebelo [1], we note that the matrix H can be written in the form

$$H=\begin{bmatrix} 1 & \frac{e^{i\phi_{12}}(1+e^{-i\theta_3}+e^{-i\theta_4})}{3} & \frac{e^{i\phi_{13}}(1+e^{-i\theta_2}+e^{-i(\theta_1-\theta_4)})}{3} \\ \frac{e^{-i\phi_{12}}(1+e^{i\theta_3}+e^{i\theta_4})}{3} & 1 & \frac{e^{-i(\phi_{12}-\phi_{13})}(e^{-i(\theta_1-\theta_4)}+e^{i\theta_4}+e^{-i(\theta_2-\theta_3)})}{3} \\ \frac{e^{-i\phi_{13}}(1+e^{i\theta_2}+e^{i(\theta_1-\theta_4)})}{3} & \frac{e^{i(\phi_{12}-\phi_{13})}(e^{i(\theta_1-\theta_4)}+e^{-i\theta_4}+e^{i(\theta_2-\theta_3)})}{3} & 1 \end{bmatrix}\ . \quad (2.8)$$

As the discussion above shows, the θ variables are small. We can then write

$$\tfrac{1}{3}(e^{ix_1\epsilon}+e^{ix_2\epsilon}+e^{ix_3\epsilon})\simeq(1-X)e^{i\zeta\epsilon}\ , \quad (2.9)$$

where, as we shall describe in more detail in Sec. III, X is positive but small compared to 1, and the phase $\zeta\epsilon$ is likewise small; indeed ζ is given to leading order by

$$\zeta\simeq\tfrac{1}{3}(x_1+x_2+x_3)\ . \quad (2.10)$$

When we apply this to Eq. (2.8), we find

$$H=\begin{bmatrix} 1 & (1-a)e^{i(\phi_{12}+\alpha)} & (1-b)e^{i(\phi_{13}+\beta)} \\ (1-a)e^{-i(\phi_{12}+\alpha)} & 1 & (1-c)e^{i(-\phi_{12}+\phi_{13}+\delta)} \\ (1-b)e^{-i(\phi_{13}+\beta)} & (1-c)e^{i(-\phi_{12}+\phi_{13}+\delta)} & 1 \end{bmatrix}\ . \quad (2.11)$$

---

[2]If it should be desirable to keep diagonal phase angles, then we set $\theta_1=\phi_{23}+\phi_{32}-\phi_{33}-\phi_{22}$; $\theta_2=\phi_{13}+\phi_{31}-\phi_{33}-\phi_{11}$; $\theta_3=\phi_{12}+\phi_{21}-\phi_{22}-\phi_{11}$; $\theta_4=\phi_{12}-\phi_{12}+\phi_{23}-\phi_{22}$.

The leading behavior of the phases α, β, and δ are

$$\alpha \simeq -\tfrac{1}{3}(\theta_3+\theta_4) , \tag{2.12a}$$

$$\beta \simeq -\tfrac{1}{3}(\theta_1+\theta_2-\theta_4) , \tag{2.12b}$$

$$\delta \simeq -\tfrac{1}{3}(\theta_1+\theta_2-\theta_3-2\theta_4) . \tag{2.12c}$$

We now apply a unitary transformation U_1:

$$U_1=\begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i(\phi_{12}+\alpha)} & 0 \\ 0 & 0 & e^{i(\phi_{13}+\beta)} \end{bmatrix} . \tag{2.13}$$

Then

$$H' \equiv U_1 H U_1^{-1} = \begin{bmatrix} 1 & (1-a) & (1-b) \\ (1-a) & 1 & (1-c)e^{i\Omega} \\ (1-b) & (1-c)e^{-i\Omega} & 1 \end{bmatrix} , \tag{2.14}$$

where the phase in the 23 and 32 elements is

$$\Omega \equiv \alpha-\beta+\delta . \tag{2.15}$$

Equations (2.12) show immediately that Ω is zero to first order in the θ_i; we shall see in Sec. III that Ω is at most $O(\epsilon^3)$.

III. PERTURBATIVE EXPANSION

Let us suppose that in any one sector the theta variables are of order ϵ. We can then expand the factors involving these quantities in powers of ϵ:

$$\frac{1}{3}(e^{ix_1\epsilon}+e^{ix_2\epsilon}+e^{ix_3\epsilon}) \simeq (1-X_2\epsilon^2+X_4\epsilon^4+\cdots)e^{i(\zeta_1\epsilon+\zeta_3\epsilon^3+\cdots)} . \tag{3.1}$$

The absence of odd powers in the magnitude and even powers in the phases is a general feature of this expansion. We calculate

$$X_2=\frac{1}{9}(x_1^2+x_2^2+x_3^2-x_1x_2-x_1x_3-x_2x_3) , \tag{3.2a}$$

$$\zeta_1=\frac{1}{3}(x_1+x_2+x_3) . \tag{3.2b}$$

The quantity X_2 is non-negative. We do not specify X_4 and ζ_3 because they generally depend on higher order terms in the theta variables.

We can apply this expansion to H', noting that $\Omega=\alpha_3-\beta_3+\delta_3$, and that $a=a_2\epsilon^2+a_4\epsilon^4$, and similarly for b and c. The mass hierarchy imposes some useful relations and limits among the variables a, b, c, and Ω and their perturbative elements. We use the invariants of H':

$$w_1w_2+w_1w_3+w_2w_3=3-(1-a)^2-(1-b)^2-(1-c)^2 , \tag{3.3}$$

$$w_1w_2w_3=1-(1-a)^2-(1-b)^2-(1-c)^2 +2(1-a)(1-b)(1-c)\cos\Omega . \tag{3.4}$$

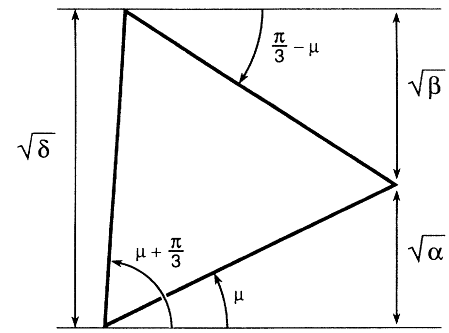

FIG. 1. Triangle relations for the quantities a_2, b_2, and c_2.

(We use the trace invariant only to replace w_3 by $3-w_1+w_2$.) Combining these two equations, we can replace the second of them by

$$\Delta(a,b,c)=-w_1w_2w_3-2abc -2(1-a)(1-b)(1-c)(1-\cos\Omega) \tag{3.5}$$

where Δ is the triangle function, $\Delta(x,y,z)=x^2+y^2+z^2-2(xy+xz+yz)$.

With w_2 $O(\epsilon^2)$ and w_1 $O(\epsilon^2)$, we can compare the leading orders in Eqs. (3.3) to (3.5). The leading term in Eq. (3.3) is $O(\epsilon^2)$:

$$\tfrac{3}{2}w_2=a_2+b_2+c_2 . \tag{3.6}$$

The leading term in Eq. (3.5) is $O(\epsilon^4)$:

$$\Delta(a_2,b_2,c_2)=0 . \tag{3.7}$$

Equations (3.6) and (3.7) are two constraints that allow us to characterize the three quantities a_2, b_2, and c_2 by the one-parameter form

$$a_2=w_2\sin^2(\mu) , \tag{3.8a}$$

$$b_2=w_2\sin^2\left(\mu-\frac{\pi}{3}\right) , \tag{3.8b}$$

$$c_2=w_2\sin^2\left(\mu+\frac{\pi}{3}\right) . \tag{3.8c}$$

Figure 1 illustrates this triangle as well as the relation $\sqrt{c_2}=\sqrt{a_2}-\sqrt{b_2}$ that follows from it.

IV. DIAGONALIZATION AND THE CKM MATRIX

We have described elsewhere [4] how the parameters of matrices of the form H', as in Eq. (2.14), can be fit simultaneously to the observed masses and the observed values of V. The Cabibbo-Kabayashi-Maskawa matrix V can be formed from the unitary transformations U_u and U_d that diagonalize the mass squared matrices in the up and down sectors, respectively. In particular, if UHU^{-1} is the diagonalized mass squared matrix, then $V=U_uU_d^{-1}$. The rows of U are the (normalized) eigenvectors of H.

Let us denote the jth eigenvector of $H'|_d$ by $\{v_{j1}, v_{j2},$

$v_{j3}\}$, and the complex conjugate of the jth eigenvector of $H'|_u$ by $\{u_{j1}, u_{j2}, u_{j3}\}$. Then V is

$$V=\begin{bmatrix} u_{11} & u_{12} & u_{13} \\ u_{21} & u_{22} & u_{23} \\ u_{31} & u_{32} & u_{33} \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-iK} & 0 \\ 0 & 0 & e^{-iL} \end{bmatrix}\begin{bmatrix} v_{11} & v_{21} & v_{31} \\ v_{12} & v_{22} & v_{32} \\ v_{13} & v_{23} & v_{33} \end{bmatrix} . \tag{4.1}$$

The central diagonal matrix, containing the two independent parameters K and L, is the result of the successive diagonal transformations $U_2^u U_1^u U_1^{d\dagger} U_2^{d\dagger}$. We have[3]

$$K=(\phi_{12}+\alpha_1+\alpha_2)|_d-(\phi_{12}+\alpha_1+\alpha_2)|_u\equiv k_d-k_u \tag{4.2}$$

and

$$L=(\phi_{13}+\beta_1+\beta_2)|_d-(\phi_{13}+\beta_1+\beta_2)|_u\equiv l_d-l_u . \tag{4.3}$$

Reference [4] describes allowed values of the parameters a, b, c, and Ω for each sector as well as the quantities k and l consistent with masses and the known values of V. Note that k_d and k_l are not separately determined.

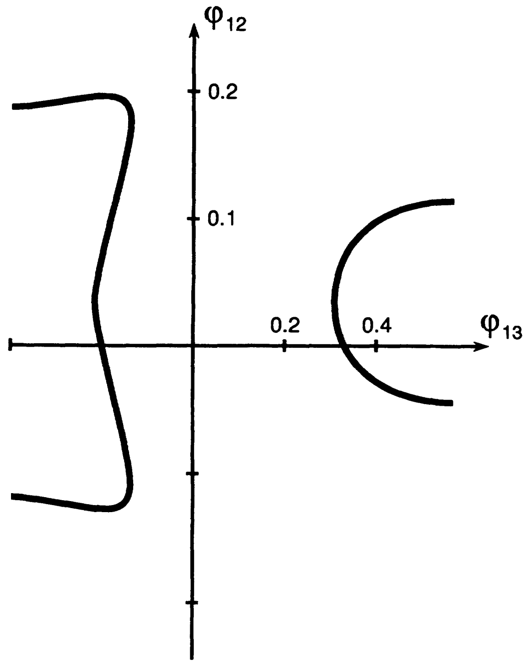

FIG. 2. Relation between the angles ϕ_{12} and ϕ_{13} that follow from Eq. (5.9) with remaining parameters those of the example in Ref. [2]. The values of those parameters are of no special interest in this purely illustrative plot. At some locations of ϕ_{13} several values of ϕ_{12} are allowed.

V. CONVERSION TO ORIGINAL PARAMETER SPACE

Let us make explicit the correspondence between the parameters we have used in order to fit [4] the magnitudes of the elements of V and the original phase angles of the ansatz. We find a set of angles, including a unique set of the θ_i, corresponding to the fitted parameters. To do so, we work within a given sector; a subscript for the sector should be understood. We compare the matrix elements that follow from the original form of H, Eq. (2.8), with the form in terms of the fitting parameters, Eq. (2.11). (We assume the ambiguity in finding say, k_d and k_l separately in terms of the phenomenological parameter k has been resolved as we like.) We have three complex equations for the three nontrivial matrix elements:[4]

$$(1-a)e^{ik}=e^{i\phi_{12}}(1+e^{-i\theta_3}+e^{-i\theta_4}) , \tag{5.1a}$$

$$(1-b)e^{il}=e^{i\phi_{13}}(1+e^{-i\phi_2}+e^{-i(\theta_1-\theta_4)}) , \tag{5.1b}$$

$$(1-c)e^{in}=e^{-i(\phi_{12}-\phi_{13})}(e^{-i(\theta_1-\theta_4)}+e^{i\theta_4}+e^{-i(\theta_2-\theta_3)}) . \tag{5.1c}$$

These represent six real equations for the six quantities $\theta_1, \ldots, \theta_4$, ϕ_{12}, and ϕ_{13} in terms of the phenomenological quantities a,b,c,k,l,n.

A perturbative view of this system reveals that to leading order ϕ_{12} and ϕ_{13} are not separately determined. In addition to the $O(\epsilon)$ quantities we have so far used, we note that a fit to the CKM matrix implies that k and l are both $O(\epsilon)$, so that ϕ_{12} and ϕ_{13} are also[5] $O(\epsilon)$. Let us set $k'\equiv k-\phi_{12}$, $l'\equiv l-\phi_{13}$, $n'\equiv n-(\phi_{13}-\phi_{12})$. These quantities are also $O(\epsilon)$, as are all θ variables, while we recall that a, b, and c are each $O(\epsilon^2)$. Then the $O(\epsilon)$ and $O(\epsilon^2)$ terms in Eqs. (5.1) give the six equations

$$k'=-(\theta_3+\theta_4)/3 , \tag{5.2a}$$

$$2a+k'^2=(\theta_3^2+\theta_4^2)/3 , \tag{5.2b}$$

$$l'=-[(\theta_1-\theta_4)+\theta_2]/3 , \tag{5.3a}$$

$$2b+1'^2=[(\theta_1-\theta_4)^2+\theta_2^2]/3 , \tag{5.3b}$$

$$n'=-[(\theta_1-\theta_4)+\theta_2-\theta_3-\theta_4]/3 , \tag{5.4a}$$

$$2c+n'^2=[(\theta_1-\theta_4)^2+\theta_2^2-2\theta_2\theta_3+\theta_3^2+\theta_4^2]/3 . \tag{5.4b}$$

Equations (5.2) can be solved for θ_3 and θ_4 in terms of k' and a; similarly Eqs. (5.3) can be solved for $\theta_1-\theta_4$ and θ_2 in terms of l' and b:

$$\theta_3=\tfrac{1}{2}[-\sqrt{3}\sqrt{4a-k'^2}-3k'] , \tag{5.5}$$

$$\theta_4=\tfrac{1}{2}[\sqrt{3}\sqrt{4a-k'^2}-3k'] , \tag{5.6}$$

or $\theta_3\leftrightarrow\theta_4$, and

[3]With diagonal elements present, replace ϕ_{12} with $\phi_{12}-\phi_{22}$ in Eq. (4.2) and ϕ_{13} with $\phi_{13}-\phi_{33}$ in Eq. (4.3).

[4]With nonzero diagonal phases, replace $\phi_{12}-\phi_{13}$ by $\phi_{12}-\phi_{13}-\phi_{22}+\phi_{33}$ in Eq. (5.1c).

[5]This is not obviously so. The $O(\epsilon)$ in ϕ_{12} and ϕ_{13} is associated with the hierarchy present in the CKM matrix V and with the small size of the CP-violating parameter J.

$$\theta_1-\theta_4=\tfrac{1}{2}[-\sqrt{3}\sqrt{4b-l'^2}-3l'] , \quad (5.7)$$

$$\theta_2=\tfrac{1}{2}[\sqrt{3}\sqrt{4b-l'^2}-3l'] , \quad (5.8)$$

or $(\theta_1-\theta_4)\leftrightarrow\theta_2$.

When these results are inserted in Eq. (5.4a) we find

$$n'=l'-k' .$$

The quantities ϕ_{12} and ϕ_{13} drop out of this equation, which becomes our earlier result that Ω contains no $O(\epsilon)$ contributions. The remaining $O(\epsilon^2)$ equation, Eq. (5.4b) is a single constraining relating ϕ_{12} and ϕ_{13}, which when we substitute $n'=l'-k'$ can be written in the form

$$a+b-c=-\tfrac{1}{4}[\sqrt{(4b-l'^2)(4a-k'^2)}-\sqrt{3}l'\sqrt{41-k'^2} -\sqrt{3}k'\sqrt{4b-l'^2}+k'l'] , \quad (5.9)$$

where we should recall k', and l', and n' are defined in terms of k, l, n, and phases ϕ_{ij}. We can then, for example, solve for ϕ_{12} in terms of ϕ_{13}. The result, which has several solutions, is plotted in Fig. 2 for the values of a,b,c,n,k,l of the example cited in Ref. [2].

VI. CONCLUSIONS

We have described the parameter space over which the pure-phase mass matrix can be made compatible with quark masses and mixing angles at present energies. It is worth emphasizing that, even within the restriction of the mass hierarchy, a large region of the parameter space remains available. We refer to Ref. [4] for a more complete description of the fitting procedure.

The term "texture" has recently been used to describe mass matrices with zeros in both the up and down sectors. This description is not appropriate in a democratic basis, and we prefer to use the term texture to describe more broadly mass matrices with reduced parameter sets; for example, the mass matrix may be symmetric, or certain elements may be simply related to one another. Thus mass matrices with texture have predictive power. While textured mass matrices may not be applicable at present energies, it is entirely possible that texture may appear at high energies, where some unifying symmetry is present. The presence of such texture can be tested [5] by running physical quantities back tc present energies. The question of texture in the context of the democratic basis in general and of the pure-phase mass matrix in particular is worth further study.

ACKNOWLEDGMENTS

We thank the Aspen Center for Physics for its hospitality. P.M.F. was supported in part by the U.S. Department of Energy under Grant No. DE-AS05-89ER40518. P.M.F. also thanks the members of the Laboratoire de Physique Théorique et Hautes Energies, Université de Paris-Sud, for their hospitality.

[1] G. C. Branco, J. I. Silva-Marcos, and M. N. Rebelo, Phys. Lett. B **237**, 446 (1990).

[2] J. Kalinowski and M. Olechowski, Phys. Lett. B **251**, 584 (1990).

[3] Y. Nambu, in *Proceedings of the International Workshop on Electroweak Symmetry Breaking,* Hiroshima, Japan, 1991, edited by W. Bardeen, J. Kodaira, and T. Muta (World Scientific, Singapore, 1992), p. 1, and references cited therein; P. Kaus and S. Meshkov, Phys. Rev. D **42**, 1863 (1990), and references cited therein.

[4] P. M. Fishbane and P. Kaus, Phys. Rev. D (to be published).

[5] S. Dimopoulos, L. J. Hall, and S. Raby, Phys. Rev. D **45**, 4192 (1992); H. Arason, D. J. Castano, P. Ramond, and E. J. Piard, *ibid.* **47**, 232 (1992); P. Ramond, R. G. Roberts, and G. G. Ross, University of Florida report (unpublished).