MASS HIERARCHIES, HIDDEN SYMMETRY AND MAXIMAL CP–VIOLATION

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In view of the observed strong hierarchy of the quark and lepton masses and of the flavor mixing angles it is argued that the description of flavor mixing must take this into account. One particular interesting way to describe the flavor mixing, which, however, is not the one used today, emerges, which is particularly suited for models of quark mass matrices based on flavor symmetries. We conclude that the unitarity triangle important for B physics should be close to or identical to a rectangular triangle. CP violation is maximal in this sense.

At the magnificent Boston Museum of Fine Arts one can see a big stone brought in from Northern Africa, covered with strange hieroglyphs. More than 2000 years ago it located in the Great Temple of Amun at the old City of Jebel Barkal in the kingdom of Nubia and is assumed to describe the rulership of king Tanyidamani. The text is written in the Meroitic language, which is still underdeciphered. Neither the grammar of that language nor the content of the text on the Stone of Amun is known, only the letters.

In particle physics today one is facing a similar problem, as far as the masses of the leptons and quarks are concerned. After the discovery of the t–quark the spectrum of these masses (apart from the yet unknown neutrino masses) is known. It is a rather wild spectrum, extending over 5 orders of magnitude, from the tiny electron mass to the huge $t$–mass, but the actual dynamics behind this spectrum remains mysterious. Nature speaks to us in some kind of Meroitic language. The letters of this language, i.e. the masses and flavor mixing parameters, are known, but the grammar and the content of the text is unknown. Of course, in my talk I cannot offer a complete solution of the mass problem, but I shall describe what I would like to define as the grammar of patterns and rules, which are not only very simple, but seem to come out very well, if confronted with the experimental results.

Let me remind you, just for illustration, of the observed eigenvalues of the quark masses. Typical numbers are, at a renormalization point of

$$\mu = m_t (\approx 175)$$

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These masses are, of course, just eigenvalues of the quark mass matrices, which in the Standard Model are introduced by the coupling of the quark fields to the scalar field.

The phenomenon of flavor mixing arises due to the observed fact that the $W$-boson, after interacting with a mass eigenstate, produces a state, which is a mixture of all three quark mass eigenstates of the same electric charge. Thus a $u$-quark, for example, is transformed primarily into a $d$-quark (with a probability of about 95%), sometimes into a $s$-quark (probability about 5%), and occasionally (probability about $10^{-5}$) into a $b$-quark, provided that the energy transfer is large enough. This mismatch between the $U$-sector and the $D$-sector of the quarks is usually parametrized by the CKM mixing matrix $V_{\text{CKM}}$.

The phenomenon of flavor mixing, which is intrinsically linked to $CP$-violation, is an important ingredient of the Standard Model of Basic Interactions. Yet unlike other features of the Standard Model, e. g. the mixing of the neutral electroweak gauge bosons, it is a phenomenon which can merely be described. A deeper understanding is still lacking, but most theoreticians would agree that it is directly linked to the mass spectrum of the quarks – the possible mixing of lepton flavors will not be discussed here. Furthermore there is a general consensus that a deeper dynamical understanding would require to go beyond the physics of the Standard Model. In this talk I shall not go thus far. Instead I shall demonstrate that the observed properties of the flavor mixing, combined with our knowledge about the quark mass spectrum, suggest specific symmetry properties which allow to fix the flavor mixing parameters with high precision, thus predicting the outcome of the experiments which will soon be performed at the $B$-meson factories.

In the standard electroweak theory the phenomenon of flavor mixing of the quarks is described by the $3 \times 3$ unitary CKM-matrix. This matrix can be expressed in terms of four parameters, which are usually taken as three rotation angles and one phase.

In the standard model the generation of quark masses is intimately related to the phenomenon of flavor mixing. In particular, the flavor mixing parameters do depend on the elements of quark mass matrices. A particular structure of the underlying mass matrices calls for a particular choice of the parametrization of the flavor mixing matrix. For example, in ref. (3) it was noticed that a rather special form of the flavor mixing matrix results, if one starts from Hermitian mass matrices in which the $(1,3)$ and $(3,1)$ elements vanish. This has been subsequently observed again in a number of papers.
Recently we have studied the exact form of such a description from a general point of view and pointed out some advantages of this type of representation in the discussion of flavor mixing and $CP$-violating phenomena, which will be discussed later.

In the standard model the weak charged currents are given by

$$
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
d \\
s \\
b
\end{pmatrix}_L,
$$

(2)

where $u$, $c$, ..., $b$ are the quark mass eigenstates, $L$ denotes the left-handed fields, and $V_{ij}$ are elements of the CKM matrix $V$. In general $V_{ij}$ are complex numbers, but their absolute values are measurable quantities. For example, $|V_{cb}|$ primarily determines the lifetime of $B$ mesons. The phases of $V_{ij}$, however, are not physical, like the phases of quark fields. A phase transformation of the $u$ quark ($u \rightarrow u e^{i\alpha}$), for example, leaves the quark mass term invariant but changes the elements in the first row of $V$ (i.e., $V_{uj} \rightarrow V_{uj} e^{-i\alpha}$). Only a common phase transformation of all quark fields leaves all elements of $V$ invariant, thus there is a five-fold freedom to adjust the phases of $V_{ij}$.

In general the unitary matrix $V$ depends on nine parameters. Note that in the absence of complex phases $V$ would consist of only three independent parameters, corresponding to three (Euler) rotation angles. Hence one can describe the complex matrix $V$ by three angles and six phases. Due to the freedom in redefining the quark field phases, five of the six phases in $V$ can be absorbed and we arrive at the well-known result that the CKM matrix $V$ can be parametrized in terms of three rotation angles and one $CP$-violating phase.

Recently it was shown that one way to describe the mixing of three families is particularly useful. It is given as follows:

$$
V =
\begin{pmatrix}
c_u & s_u & 0 \\
-s_u & c_u & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
e^{-i\phi} & 0 & 0 \\
0 & c & s \\
0 & -s & c
\end{pmatrix}
\begin{pmatrix}
c_d & -s_d & 0 \\
s_d & c_d & 0 \\
0 & 0 & 1
\end{pmatrix}
$$

$$
= \begin{pmatrix}
s_u s_d c + c_u c_d e^{-i\phi} & s_u c_d c - c_u s_d e^{-i\phi} & s_u s \\
s_u s_d c - c_u c_d e^{-i\phi} & c_u c_d c + s_u s_d e^{-i\phi} & c_u s \\
-s_d s & -c_d s & c
\end{pmatrix},
$$

(3)

The three angles $\theta_u$, $\theta_d$ and $\theta$ in Eq. (2) can all be arranged to lie in the first quadrant through a suitable redefinition of quark field phases. Consequently all $s_u$, $s_d$, $s$ and $c_u$, $c_d$, $c$ are positive. The phase $\phi$ can in general take values from 0 to $2\pi$; and $CP$ violation is present in weak interactions if $\phi \neq 0, \pi$ and $2\pi$. 


In comparison with all other parametrizations discussed previously, the one given here has a number of interesting features which in our view make it very attractive and provide strong arguments for its use in future discussions of flavor mixing phenomena, in particular, those in B-meson physics. We shall discuss them below.

a) As shown in ref. (5), the flavor mixing matrix $V$ in Eq. (12) follows directly from the chiral expansion of the mass matrices. Thus it naturally takes into account the hierarchical structure of the quark mass spectrum.

b) The complex phase describing CP violation ($\varphi$) appears only in the $(1,1)$, $(1,2)$, $(2,1)$ and $(2,2)$ elements of $V$, i.e., in the elements involving only the quarks of the first and second families. This is a natural description of CP violation since in our hierarchical approach CP violation is not directly linked to the third family, but rather to the first and second ones, and in particular to the mass terms of the $u$ and $d$ quarks.

It is instructive to consider the special case $s_u = s_d = s = 0$. Then the flavor mixing matrix $V$ takes the form

$$V = \begin{pmatrix} e^{-i\varphi} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}. \quad (4)$$

This matrix describes a phase change in the weak transition between $u$ and $d$, while no phase change is present in the transitions between $c$ and $s$ as well as $t$ and $b$. Of course, this effect can be absorbed in a phase change of the $u$- and $d$-quark fields, and no CP violation is present. Once the angles $\theta_u$, $\theta_d$ and $\theta$ are introduced, however, CP violation arises. It is due to a phase change in the weak transition between $u'$ and $d'$, where $u'$ and $d'$ are the rotated quark fields, obtained by applying the corresponding rotation matrices given in Eq. (12) to the quark mass eigenstates ($u'$: mainly $u$, small admixture of $c$; $d'$: mainly $d$, small admixture of $s$).

c) The dynamics of flavor mixing can easily be interpreted by considering certain limiting cases in Eq. (8). In the limit $\theta \to 0$ (i.e., $s \to 0$ and $c \to 1$), the flavor mixing is, of course, just a mixing between the first and second families, described by only one mixing angle (the Cabibbo angle $\theta_C$). It is a special and essential feature of the representation (8) that the Cabibbo angle is not a basic angle, used in the parametrization. The matrix element $V_{us}$ (or $V_{cd}$) is indeed a superposition of two terms including a phase. This feature arises naturally in our hierarchical approach, but it is not new. In many models of specific textures of mass matrices, it is indeed the case that the Cabibbo-type transition $V_{us}$ (or $V_{cd}$) is a superposition of several terms. At first, it was obtained by me in the discussion of the two-family mixing, and in various
studies of quark mass matrices.

In the limit $\theta = 0$ considered here, one has $|V_{us}| = |V_{cd}| = \sin \theta_C \equiv s_C$ and

$$s_C = |s_u c_d - c_u s_d e^{-i \varphi}|.$$  

(5)

This relation describes a triangle in the complex plane which we shall denote as the “LQ–triangle” (“light quark triangle”). This triangle is a feature of the mixing of the first two families. Explicitly one has (for $s = 0$):

$$\tan \theta_C = \frac{\tan^2 \theta_u + \tan^2 \theta_d - 2 \tan \theta_u \tan \theta_d \cos \varphi}{1 + \tan^2 \theta_u \tan^2 \theta_d + 2 \tan \theta_u \tan \theta_d \cos \varphi}. \quad (6)$$

Certainly the flavor mixing matrix $V$ cannot accommodate $CP$ violation in this limit. However, the existence of $\varphi$ seems necessary in order to make Eq. (6) compatible with current data, as one can see below.

d) The three mixing angles $\theta$, $\theta_u$ and $\theta_d$ have a precise physical meaning. The angle $\theta$ describes the mixing between the second and third families. We shall refer to this mixing involving $t$ and $b$ as the “heavy quark mixing”. The angle $\theta_u$, however, describes the $u$-$c$ mixing, and we shall denote this as the “$u$-channel mixing”. The angle $\theta_d$ describes the $d$-$s$ mixing: it will be denoted as the “$d$-channel mixing”. Thus there exists an asymmetry between the mixing of the first and second families and that of the second and third families, which in our view reflects interesting details of the underlying dynamics of flavor mixing. The heavy quark mixing is a combined effect, involving both charge $+2/3$ and charge $-1/3$ quarks, while the $u$- or $d$-channel mixing (described by the angle $\theta_u$ or $\theta_d$) proceeds solely in the charge $+2/3$ or charge $-1/3$ sector. Therefore a precise experimental determination of these two angles would allow to draw interesting conclusions about the amount and perhaps the underlying pattern of the $u$- or $d$-channel mixing.

e) The three angles $\theta$, $\theta_u$ and $\theta_d$ are related in a very simple way to observable quantities of $B$-meson physics. For example, $\theta$ is related to the rate of the semileptonic decay $B \to D^* \ell \nu$; $\theta_u$ is associated with the ratio of the decay rate of $B \to (\pi, \rho) \ell \nu$ to that of $B \to D^* \ell \nu$; and $\theta_d$ can be determined from the ratio of the mass difference between two $B_d$ mass eigenstates to that between two $B_s$ mass eigenstates. We find the following exact relations:

$$\sin \theta = |V_{cb}| \sqrt{1 + \frac{|V_{ub}|^2}{|V_{cb}|^2}}, \quad (7)$$

and

$$\tan \theta_u = \frac{|V_{ub}|}{|V_{cb}|},$$

5
These simple results make our parametrization (8) uniquely favorable for the study of $B$-meson physics.

By use of current data on $|V_{ub}|$ and $|V_{cb}|$, i.e., $|V_{cb}| = 0.039 \pm 0.002$ and $|V_{ub}/V_{cb}| = 0.08 \pm 0.02$, we obtain $\theta_u = 4.57^\circ \pm 1.14^\circ$ and $\theta = 2.25^\circ \pm 0.12^\circ$. Taking $|V_{td}| = (8.6 \pm 2.1) \times 10^{-4}$, which was obtained from the analysis of current data on $B_0^d-\bar{B}_0^d$ mixing, we get $|V_{td}/V_{ts}| = 0.22 \pm 0.07$, i.e., $\theta_d = 12.7^\circ \pm 3.8^\circ$. Both the heavy quark mixing angle $\theta$ and the $u$-channel mixing angle $\theta_u$ are relatively small. Recently a fit of these angles was made, with rather small uncertainties for the angles and the phase $\phi$.

$$\varphi = \arccos \left( \frac{s_u c_d c^2 + c_u s_d^2 - |V_{us}|^2}{2s_u c_u s_d c_d} \right).$$

(10)

The two-fold ambiguity associated with the value of $\varphi$, coming from $\cos \varphi = \cos(2\pi - \varphi)$, is removed if one takes $\sin \varphi > 0$ into account. More precise measurements of the angles $\theta_u$ and $\theta_d$ in the forthcoming experiments of $B$ physics will remarkably reduce the uncertainty of $\varphi$ to be determined from Eq. (10). This approach is of course complementary to the direct determination of $\varphi$ from $CP$ asymmetries in some weak $B$-meson decays into hadronic $CP$ eigenstates.

Considering the presently known phenomenological constraints (see e.g. ref. (7) that the value of $\varphi$ is most likely in the range $40^\circ$ to $120^\circ$, the central
value is $\varphi \approx 81^\circ$. Note that $\varphi$ is essentially independent of the angle $\theta$, due to the tiny observed value of the latter. Once $\tan \theta$ is precisely measured, one shall be able to fix the magnitude of $\varphi$ to a satisfactory degree of accuracy.

h) It is well–known that $CP$ violation in the flavor mixing matrix $V$ can be described by the quantity $J$:

$$\text{Im} \left( V_d V_{jm} V_{im}^* V_{jl}^* \right) = J \sum_{k,n=1}^{3} (\epsilon_{ijk} \epsilon_{lmn}) . \tag{11}$$

In our parametrisation $J$ reads

$$J = s_u c_u c_d s^2 \sin \varphi \tag{12}$$

Obviously $\varphi = 90^\circ$ leads to the maximal value of $J$. Indeed $\varphi = 90^\circ$, a particularly interesting case for $CP$ violation, is quite consistent with current data. Since in our description of the flavor mixing the complex phase $\varphi$ is related in a simple way to the phases of the quark mass terms, the case $\varphi = 90^\circ$ is especially interesting. It can hardly be an accident, and this case should be studied further. The possibility that the phase $\varphi$ describing $CP$ violation in the standard model is given by the algebraic number $\pi/2$ should be taken seriously. It may provide a useful clue towards a deeper understanding of the origin of $CP$ violation and of the dynamical origin of the fermion masses, and might be a signal for an interesting new symmetry (see also ref. (15)).

The case $\varphi = 90^\circ$ has been denoted as “maximal” $CP$ violation. It implies in our framework that in the complex plane the $u$–channel and $d$–channel mixings are perpendicular to each other. In this special case (as well as $\theta \to 0$), we have

$$\tan^2 \theta_C = \frac{\tan^2 \theta_u + \tan^2 \theta_d}{1 + \tan^2 \theta_u \tan^2 \theta_d} . \tag{13}$$

To a good approximation (with the relative error $\sim 2\%$), one finds $s^2_\varphi \approx s^2_u + s^2_d$.

h) At future $B$-meson factories, the study of $CP$ violation will concentrate on measurements of the unitarity triangle

$$S_u + S_c + S_l = 0 , \tag{14}$$

where $S_l \equiv V_{ld} V_{lb}^*$ in the complex plane. The inner angles of this triangle are as usual given by:

$$\alpha \equiv \text{arg}(-S_l S_u^*) ,$$
$$\beta \equiv \text{arg}(-S_c S_l^*) ,$$
$$\gamma \equiv \text{arg}(-S_u S_c^*) . \tag{15}$$
In terms of the parameters $\theta$, $\theta_u$, $\theta_d$ and $\varphi$, we obtain

$$\sin(2\alpha) = \frac{2c_u c_d \sin \varphi (s_u s_d c + c_u c_d \cos \varphi)}{s_u^2 s_d^2 c^2 + c_u^2 c_d^2 + 2s_u c_u s_d c_d \cos \varphi},$$

$$\sin(2\beta) = \frac{2s_u c_d \sin \varphi (c_u s_d c - s_u c_d \cos \varphi)}{c_u^2 s_d^2 c^2 + s_u^2 c_d^2 - 2s_u c_u s_d c_d \cos \varphi}. \quad (16)$$

To an excellent degree of accuracy, one finds $\alpha \approx \varphi$. In order to illustrate how accurate this relation is, let us use the central values of $\theta$, $\theta_u$ and $\theta_d$ (i.e., $\theta = 2.25^\circ$, $\theta_u = 4.57^\circ$ and $\theta_d = 12.7^\circ$). Then one arrives at $\varphi - \alpha \approx 1^\circ$ as well as $\sin(2\alpha) \approx 0.34$ and $\sin(2\beta) \approx 0.65$. It is expected that $\sin(2\alpha)$ and $\sin(2\beta)$ will be directly measured from the CP asymmetries in $B_d \to \pi^+\pi^-$ and $B_d \to J/\psi K_S$ modes at a $B$-meson factory.

Note that the three sides of the unitarity triangle can be rescaled by $|V_{cb}|$. In a very good approximation (with the relative error $\sim 2\%$), one arrives at

$$|S_u| : |S_c| : |S_t| \approx s_u c_d : s_C : s_d. \quad (17)$$

Equivalently, one can obtain

$$s_\alpha : s_\beta : s_\gamma \approx s_C : s_u c_d : s_d, \quad (18)$$

where $s_\alpha \equiv \sin \alpha$, etc. Comparing this triangle with the LQ-triangle we find that they are indeed congruent with each other to a high degree of accuracy. The congruent relation between these two triangles is particularly interesting, since the LQ-triangle is essentially a feature of the physics of the first two quark families, while the unitarity triangle by definition is linked to all three families. In this connection it is of special interest to note that in models which specify the textures of the mass matrices the Cabibbo triangle and hence the three angles of the unitarity triangle can be fixed by the spectrum of the light quark masses and the CP-violating phase $\varphi$.

j) Compared with the standard parametrization of the flavor mixing matrix $V$ the parametrization discussed here has an additional advantage: the renormalization-group evolution of $V$, from the weak scale to an arbitrary high energy scale, is to a very good approximation associated only with the angle $\theta$. This can easily be seen if one keeps the $t$ and $b$ Yukawa couplings only and neglects possible threshold effects in the one-loop renormalization-group equations of the Yukawa matrices. Thus the parameters $\theta_u$, $\theta_d$ and $\varphi$ are essentially independent of the energy scale, while $\theta$ does depend on it and will change if the underlying scale is shifted, say from the weak scale ($\sim 10^2$ GeV) to the grand unified theory scale (of order $10^{16}$ GeV). In short, the heavy quark
mixing is subject to renormalization-group effects; but the u- and d-channel mixings are not, likewise the phase \( \varphi \) describing \( CP \) violation and the LQ-triangle as a whole. It follows that only the angle \( \theta \), but not \( \Theta_u, \Theta_d \) or \( \varphi \), depends in its behaviour on the reference energy scale and is increased on the underlying model, e. g. on whether there is a supersymmetric extension of the Standard Model or not.

We have presented a new description of the flavor mixing phenomenon, which is based on the phenomenological fact that the quark mass spectrum exhibits a clear hierarchy pattern. This leads uniquely to the interpretation of the flavor mixing in terms of a heavy quark mixing, followed by the u-channel and d-channel mixings. The complex phase \( \varphi \), describing the relative orientation of the u-channel mixing and the d-channel mixing in the complex plane, signifies \( CP \) violation, which is a phenomenon primarily linked to the physics of the first two families. The Cabibbo angle is not a basic mixing parameter, but given by a superposition of two terms involving the complex phase \( \varphi \). The experimental data suggest that the phase \( \varphi \), which is directly linked to the phases of the quark mass terms, is close to \( 90^\circ \). This opens the possibility to interpret \( CP \) violation as a maximal effect, in a similar way as parity violation.

Our description of flavor mixing has many clear advantages compared with other descriptions. We propose that it should be used in the future description of flavor mixing and \( CP \) violation, in particular, for the studies of quark mass matrices and \( B \)-meson physics.

The description of the flavor mixing phenomenon given above is of special interest if for the \( U \) and \( D \) channel mixing the quark mass textures discussed first in \( 7 \) are applied (see also \( 17 \)). In that case one finds (apart from small corrections)

\[
\tan \Theta_d = \sqrt{\frac{m_d}{m_s}}
\]

(19)

\[
\tan \Theta_u = \sqrt{\frac{m_u}{m_c}}.
\]

The experimental value for \( \tan \Theta_u \) given by the ratio \( V_{ub}/V_{cb} \) is in agreement with the observed value for \( (m_u/m_c)^{1/2} \approx 0.07 \), but the errors for both \( (m_u/m_c)^{1/2} \) and \( V_{ub}/V_{cb} \) are comparable (about 25%).

The angle \( \Theta_d \) is expected to be about \( 12.6^\circ \), if we use a mass ratio \( m_s/m_d \approx 20 \), as obtained in chiral perturbation theory. This agrees well with the experimental values discussed above.

As emphasized in ref. \( 17 \), the phase angle \( \varphi \) is very close to \( 90^\circ \), implying that the LQ-triangle and the unitarity triangle are essentially rectangular.
triangles. In particular the angle $\beta$ which is likely to be measured soon in the study of the reaction $B^0 \to J/\psi K^*_s$ is expected to be close to 20°.

It will be very interesting to see whether the angles $\Theta_d$ and $\Theta_u$ are indeed given by the square roots of the light quark mass ration $m_d/m_s$ and $m_u/m_c$, which imply that the phase $\varphi$ is close to or exactly 90°. This would mean that the light quarks play the most important rôle in the dynamics of flavor mixing and $CP$ violation.
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