The rephasing freedom and the NNI form of quark mass matrices

Eiichi Takasugi

Department of Physics, Osaka University
1-16 Toyonaka, Osaka 560, Japan

Abstract
For three generations of quarks, we show that one of quark mass matrices can be transformed into either a Fritzsch form or a Branco-Silva-Marcos form, while the other is kept in the NNI basis. In these bases, quark mass matrices are determined unambiguously once quark masses and the CKM mixing are given.
1 Introduction

Since Fritzsch[1] introduced an so called Fritzsch ansatz for quark mass matrices, the understanding of the meaning of this ansatz has been an important issue in the research on finding the origin of the quark mixing. Branco, Lavoura and Mota[2] have shown that quark mass matrices can be transformed into the NNI (nearest neighbor interaction) form without loss of generality. They argued that the Fritzsch ansatz is realized if the hermiticity is required on masses in the NNI basis. However, it is known that the Fritzsch ansatz for both u- and down-quark mass matrices does not explain the experimental data of quark mixing. Branco and Silva-Marcos[3] proposed another ansatz in the NNI form to which we refer as a BS form. The BS form has a complimentary feature to the Fritzsch form for the quark mixing and seems to be another important ansatz. Recently, Ito[4] showed that the experimental data of the quark mixing are explained well if the Fritzsch ansatz is used for the up-quark mass matrix $M_u$ and the BS ansatz for the down-quark mass matrix. However, there is no reasonable explanation of the Branco ansatz up to now.

Recently, Koide[5] reported an interesting observation that for three generations, the 3-2 element of the up-quark mass matrix $M_{u32}$ can be made zero by using the rephasing freedom of quarks in the NNI basis. In this paper, inspired by Koide’s work[5], we investigate further the role of the rephasing freedom of quarks and its relation to the transformation explicitly. By using the rephasing freedom, we constructed explicitly the transformation of $M_u$ into the Fritzsch form while $M_d$ is kept in the NNI form (hereafter we refer to it as the Fritzsch-type basis) and also the transformation of $M_d$ into the BS form while $M_u$ is kept in the NNI basis (hereafter we refer to it as the BS-type basis). For three generations, the rephasing freedom contains two phase parameters which are adjusted to make these transformations. Phase parameters are determined by a complex equation. We analyzed this equation and found out that there exist solutions of phase parameters for reasonable mass matrices such that the experimental values of the quark mixing are reproduced. Since we deal with reasonable mass matrices in practice,
these transformations exist for all practically meaningful matrices. As a result, for three generations the Fritzsch ansatz for $M_u$ or the BS ansatz for $M_d$ in the NNI basis is not the ansatz anymore, but these can be realized by the transformation that leaves the CKM matrix invariant.

Let us define the problem clearly. Firstly, we define mass terms as $\bar{u}_L M_u u_R + \bar{d}_L M_d d_R$ and the unitary transformation for left-handed quarks and the right-handed quarks which leaved the CKM quark mixing matrix invariant:

$$\tilde{U}^\dagger M_u \tilde{V}_u = \tilde{M}_u ,$$
$$\tilde{U}^\dagger M_d \tilde{V}_d = \tilde{M}_d .$$

(1)

Here $\tilde{U}$ is the transformation matrix of left-handed quarks, $\tilde{V}_q (q = u, d)$ are transformation matrices of right-handed quarks. Branco et.al.[2] showed that by this transformation, $\tilde{M}_q$ can be made into the NNI basis,

$$\tilde{M}_q = \begin{pmatrix} 0 & a_q & 0 \\ b_q & 0 & c_q \\ 0 & d_q & e_q \end{pmatrix} .$$

(2)

Our question is to seek the possibility to transform $M_u$ or $M_d$ into some special forms by keeping the other mass matrix in the NNI form. Koide[5] pointed out that there is the rephasing freedom of quarks which we use for the above transformations. The rephasing freedom can be regarded in a different way. The unitary matrices for the transformation in Eq.(1) are $\tilde{U}$, $\tilde{V}_u$ and $\tilde{V}_d$. Each unitary matrix has six freedoms aside from unimportant phase freedoms for every column. Thus there are eighteen freedoms in the transformation. The requirement for the NNI form for mass matrices amounts to sixteen real constraints. Thus, there remain two freedoms which correspond to the rephasing freedom. Thus, we really treat the transformation in Eq.(1). This freedom is present only for three generations of quarks.

In Sec.2, we see how $M_u$ can be transformed to a Fritzsch form or how $M_d$ can be transformed to a BS form. We obtain a complex equation containing two phases for each
case. In Sec.3, we show that these equations have solutions for two phases, when mass matrices are ones which reproduce the CKM quark mixing. Summary is given in Sec.4.

2 Transformation to the Fritzsch-type or the BS-type basis

Let us start by diagonalizing quark mass matrices as

\[ U^\dagger_u M_u V_u = D_u , \quad U^\dagger_d M_d V_d = D_d , \]

(3)

where \( D_q \) is a diagonal matrix. The CKM matrix \( K \) is expressed by

\[ K = P^\dagger_u U^\dagger_u U_d P_d , \]

(4)

where \( P_q \) are diagonal phase matrices originated from the rephasing freedoms of quarks. The important observation is that \( P_q \) can not be fixed yet because they change if the phases of column vectors in unitary matrices \( U_q \) and \( V_q \) are changed. Therefore, we consider \( P_q \) are arbitrary phase matrices. This phase freedom is called the rephasing freedom by Koide[5].

Now we rewrite transformations in similar forms in Eq.(1) as

\[ U^\dagger_u M_u V_u = D_u , \quad U^\dagger_d M_d V_d = P_u K P_d^\dagger D_d , \]

(5)

or

\[ U^\dagger_d M_u V_u = P_d K P_u^\dagger D_u , \quad U^\dagger_d M_d V_d = D_d . \]

(6)

For both forms, the transformation matrix for the left-handed quarks is the same for the up- and down-quarks so that the CKM matrix is left invariant.

(a) The Fritzsch-type basis

Here, we shall transform the diagonal basis of mass matrices to the one where \( M_u \) takes the Fritzsch form as
\[(U_u O_u^T)^\dagger M_u V_u O_u^T = O_u D_u O_u^T = \tilde{M}_{uF},\]
\[(U_u O_u^T)^\dagger M_d V_d' = O_u P_u K P_d^\dagger D_d V_d' = \tilde{M}_{d}.\]

We used Eq.(5) to derive the above equation. In order for \(\tilde{M}_{uF}\) to be a Fritzsch matrix
\[\tilde{M}_{uF} = \begin{pmatrix} 0 & a_u & 0 \\ a_u & 0 & c_u \\ 0 & c_u & e_u \end{pmatrix},\]  
we chose \(O_u\) to be the orthogonal matrix which diagonalizes the \(\tilde{M}_{uF}\). Here \(a_u, c_u\) and \(e_u\) are all real parameters and are expressed by the up-quark masses, \(m_u, m_c\) and \(m_t\). Similarly, the orthogonal matrix \(O_u\) is expressed uniquely by these quark masses. \(M_d\) is transformed by introducing the unitary matrix \(V_d'\) for the right-handed down-quarks which is utilized to transform \(\tilde{M}_d\) into a NNI form.

If \(\tilde{M}_d\) can be transformed into the NNI form, then the unitary matrices to transform into the Fritzsch-type basis are readily obtained. Explicitly, by comparing Eq.(7) with Eq.(1), we find \(\tilde{U} = U_u O_u^T\), \(\tilde{V}_u = V_u O_u^T\) and \(\tilde{V}_d = V_d V_d'\). The transformation for \(M_d\) contains a unitary matrix \(V_d'\) and the phase matrix \(P_u\) which will play an important role.

Now the question is how \(\tilde{M}_d\) can be made into the NNI form,
\[\tilde{M}_d = \begin{pmatrix} 0 & a_d e^{i\alpha_1} & 0 \\ b_d & 0 & c_d e^{i\alpha_2} \\ 0 & d_d & e_d \end{pmatrix},\]  
where \(a_d, b_d, v_d, d_d\) and \(e_d\) are real nonnegative numbers. As proved by Branco et al.[2], if the condition
\[H_{d12} = 0\]  
is satisfied, \(\tilde{M}_d\) can be transformed into the NNI form by taking an appropriate \(V_d'\). Here, \(H_d\) is an hermitian matrix defined by
\[H_d \equiv \tilde{M}_d \tilde{M}_d^\dagger = O_u P_u (K D_d^2 K^\dagger) P_u^\dagger O_u^T.\]
The condition $H_{d12} = 0$ contains only phases in $P_u$ as adjustable parameters because $(KD_d^2K^\dagger)$ is written only by the observable, masses of quarks and CKM matrix elements. The condition is expressed explicitly by

$$\sum_{j,k=1,2,3} e^{i(\theta_j - \theta_k)}(O_u)_{1j}(O_u)_{2k}(KD_d^2K^\dagger)_{jk} = 0 ,$$

where we used $P_u = \text{diag}(\exp(i\theta_1), \exp(i\theta_2), \exp(i\theta_3))$. The above complex equation contains two independent phases $\theta_1 - \theta_2$ and $\theta_2 - \theta_3$ so that in general this equation is satisfied by taking appropriate values of these phases. In the next section, we see in detail that this equation is satisfied by taking appropriate values of $\theta_1 - \theta_2$ and $\theta_2 - \theta_3$.

The NNI form $\tilde{M}_d$ is given by $H_d$ as

$$a_d = \sqrt{H_{d11}}, \quad b_d = \sqrt{\frac{\det H_d}{H_{d11}H_{d33} - |H_{d13}|^2}} ,$$

$$c_d = \frac{H_{d23}\sqrt{H_{d11}}}{\sqrt{H_{d11}H_{d33} - |H_{d13}|^2}} , \quad d_d = \frac{|H_{d13}|}{\sqrt{H_{d11}}} ,$$

$$e_d = \frac{\sqrt{H_{d11}H_{d33} - |H_{d13}|^2}}{\sqrt{H_{d11}}} , \quad \alpha_1 = \text{arg} H_{d13} , \quad \alpha_2 = \text{arg} H_{d23} ,$$

where $H_{d11}, H_{d22}, H_{d33}$ and $\det H_d$ are real nonnegative numbers. Now the up-quark mass matrix is fixed only by up-quark masses and the down-quark mass matrix is given by quark masses and the CKM elements. As a result, quark mass matrices are expressed explicitly by the observable. Recently, Harayama and Okamura[6] investigated the inverse problem to express the quark mass matrices in terms of the observable. They used the NNI form of quark mass matrices which contains twelve parameters and thus the quark mass matrices contain two free parameters. The fixing of these parameters was a problem. Koide[5] succeeded to remove these freedoms by transforming into a special basis where $M_{u32} = 0$ in the NNI form, but this form was not symmetric. Our bases are symmetric ones and mass matrices are expressed unambiguously by the observable so that this form will be useful for fixing the quark mass matrices in practice.

(b) The BS-type basis
The procedure to transform $M_d$ into the BS form is essentially the same as the Fritzsch case. We make the following transformation,

\[
(U_d O_d^T)^\dagger M_d (V_d O_d^T) = O_d D_u O_d^T = \tilde{M}_{dB} ,
\]

\[
(U_d O_d^T)^\dagger M_u (V_u V_u') = O_d P_d K^\dagger P_u^\dagger D_u V_u' = \tilde{M}_u ,
\]

where $M_{dB}$ is a BS form defined by

\[
\tilde{M}_{dB} = \begin{pmatrix} 0 & a_d & 0 \\ a_d & 0 & c_d \\ 0 & c_d & e_d \end{pmatrix} \tag{15}
\]

and $O_d$ is the orthogonal matrix which diagonalizes $\tilde{M}_{dB}$ as $O_d^T \tilde{M}_{dB} O_d' = D_d$. Here, $a_d$, $c_d$ and $e_d$ are all real parameters and $\tilde{M}_u$ is an complex matrix.

If $\tilde{M}_u$ is made into the NNI form, the transformation in Eq.(1) is given by taking $\tilde{U} = U_d O_d^T$, $\tilde{V}_d = V_d O_d^T$ and $\tilde{V}_u = V_u V_u'$. $\tilde{M}_u$ becomes the NNI form by using the freedoms of $P_d$ and $V_u'$ once the condition

\[
(H_u)_{12} = 0 \tag{16}
\]

is satisfied, where

\[
H_u = \tilde{M}_u \tilde{M}_u^\dagger = O_d P_d (K^\dagger D_u^2 K) P_d^\dagger O_d^T .
\]

The requirement of $(H_u)_{12} = 0$ is

\[
\sum_{j,k=1,2,3} e^{i(\phi_j - \phi_k)} (O_d)_{1j} (O_d)_{2k} (K^\dagger D_u^2 K)_{jk} = 0 ,
\]

where we used $P_d = \text{diag}(\exp(i\phi_1), \exp(i\phi_2), \exp(i\phi_3))$. We show in the next section that by choosing appropriate values of two independent phases $\phi_1 - \phi_2$, $\phi_2 - \phi_3$, the above equation is satisfied. When we write $\tilde{M}_u$ as

\[
\tilde{M}_u = \begin{pmatrix} 0 & a_u e^{i\beta_1} & 0 \\ b_u & 0 & c_u e^{i\beta_2} \\ 0 & d_u & e_u \end{pmatrix} \tag{19}
\]

then each element and phases are expressed in terms of $H_u$ as in Eq.(13). In this basis, quark mass matrices $\tilde{M}_{dS}$ and $\tilde{M}_u$ can be expressed uniquely by quark masses and CKM mixing.
3 Examination of constraint equations

In order to examine constraint equations in Eqs. (12) and (18), we need to parameterize the CKM matrix for which we use the following form,

\[
K \simeq \begin{pmatrix}
1 - \frac{1}{2} \lambda^2 & \lambda & \sigma e^{-i\delta} \\
-\lambda & 1 - \frac{1}{2} \lambda^2 & \rho \\
\sigma' e^{i\delta'} & -\rho & 1
\end{pmatrix},
\]

(20)

where \(\sigma' = |K_{td}|\) and phase \(\delta'\) are given by

\[
\begin{align*}
\sigma' &= \sqrt{(\lambda\rho)^2 + \sigma^2 - 2\lambda\rho\sigma \cos \delta}, \\
\sigma' \cos \delta' &= \lambda\rho - \sigma \cos \delta, \\
\sigma' \sin \delta' &= -\sigma \sin \delta.
\end{align*}
\]

(21)

Here, the orders of magnitudes of parameters in CKM matrix are \(\rho = |K_{cb}| \sim O(\lambda^2)\), \(\sigma = |K_{ub}| \sim (\lambda^4)\) and \(\sigma' = |K_{td}| \sim O(\lambda^3)\). We also define the ratios of quark masses as

\[
\begin{align*}
r_d &\equiv m_d/m_s \sim O(\lambda^2), \\
r_s &\equiv m_s/m_b \sim O(\lambda^{5/2}), \\
r_u &\equiv m_u/m_c \sim O(\lambda^4), \\
r_c &\equiv m_c/m_t \sim O(\lambda^4).
\end{align*}
\]

(22)

By using these parameters, conditions are examined.

(a) The case of the Fritzsch-type basis

Firstly, we evaluate hermitian matrix \(KD_d K^\dagger\) by using quark masses and CKM parameters in the leading order of \(\lambda\). The result is as follows:

\[
\begin{align*}
(KD_d K^\dagger)_{11} &\simeq (\sigma^2 + (r_d \lambda)^2)m_b^2, \\
(KD_d K^\dagger)_{22} &\simeq (\rho^2 + r_s^2)m_b^2, \\
(KD_d K^\dagger)_{33} &\simeq m_b^2, \\
(KD_d K^\dagger)_{12} &\simeq (\rho \sigma e^{-i\delta} + r_s^2 \lambda)m_b^2, \\
(KD_d K^\dagger)_{13} &\simeq \sigma e^{-i\delta} m_b^2, \\
(KD_d K^\dagger)_{23} &\simeq \rho m_b^2.
\end{align*}
\]

(23)
The orthogonal matrix which diagonalizes the Fritzsch mass matrix for up-quarks is given by
\[
O_u \simeq \begin{pmatrix}
1 & -\sqrt{r_u} & r_c\sqrt{r_u r_c} \\
\sqrt{r_u} & 1 & \sqrt{r_c} \\
-\sqrt{r_u r_c} & -\sqrt{r_c} & 1
\end{pmatrix}
\] (24)

By keeping leading order terms, the condition in Eq.(12) is expressed as
\[
Ae^{i\theta_{12}} - Be^{i\theta_{23}} + Ce^{i(\theta_{12}+\theta_{23}-\delta)} = D ,
\] (25)
where
\[
\theta_{12} = \theta_1 - \theta_2, \quad \theta_{23} = \theta_2 - \theta_3
\]

\[
A \equiv |A|e^{-i\kappa} = \rho\sigma e^{-i\delta} + r_s^2\lambda, \quad B = \sqrt{r_u r_c}\rho, \quad C = \sqrt{r_c}\sigma, \quad D = \sqrt{r_u}(\rho^2 + r_s^2).
\] (26)

It is worthwhile to note that \(B, C, D\) are real positive numbers, while \(A\) is a complex number. By taking the absolute values of both sides of \(e^{i(\theta_{12}-\kappa)}(|A| + Ce^{i(\theta_{23}-\delta+\kappa)}) = Be^{i\theta_{23}} + D\), we find
\[
2[BD\cos\theta_{23} - |A|C\cos(\theta_{23} - \delta + \kappa)] = |A|^2 + C^2 - B^2 - D^2 .
\] (27)

This equation has a solution if the following inequality is satisfied,
\[
\left|\frac{|A|^2 + C^2 - B^2 - D^2}{2\sqrt{B^2D^2 + |A|^2C^2 - 2|A|BCD\cos(\delta - \kappa')}}\right| \leq 1 .
\] (28)

This inequality constrains the CP violation angle \(\delta\) and the absolute values of CKM matrix elements \(\lambda, \rho\) and \(\sigma\) are given. The condition is simply written as
\[
\alpha \cos^2\delta + 2\beta \cos\delta + \gamma \leq 0 ,
\] (29)
where
\[
\alpha = 4(r_s^2\lambda\rho\sigma)^2, \quad \beta = 2r_s^2\lambda\{\rho\sigma[(r_s^2\lambda)^2 + (\rho\sigma)^2 + C^2 - B^2 - D^2] + 2C(BD - \rho\sigma C)\}, \quad \gamma = [(r_s^2\lambda)^2 + (\rho\sigma)^2 + C^2 - B^2 - D^2]^2 - 4[(BD - \rho\sigma C)^2 + (r_s^2\lambda C)^2] .
\] (30)
We consider the above equation as the constraint equation for the CP violation angle \( \delta \) by giving the experimental values of \( \lambda \), \( \rho \) and \( \sigma \). There are some uncertainties in the experimental values of them. Here we take the central values to see in what region of \( \delta \), there exist solutions. We use the CKM parameters\([7]\), \( \lambda \equiv |K_{us}| = 0.2205 \), \( \rho \equiv |K_{cb}| = 0.041 \) and \( \sigma/\rho \equiv |K_{ub}|/|K_{cb}| = 0.08 \) and the running quark masses defined at \( \mu = M_Z \), \( m_u = 0.00222\, \text{GeV} \), \( m_d = 0.00442\, \text{GeV} \), \( m_s = 0.0847\, \text{GeV} \), \( m_c = 0.661\, \text{GeV} \), \( m_b = 2.996\, \text{GeV} \) and \( m_t = 180\, \text{GeV} \). Then, the constraint gives \( \cos \delta \leq 0.66 \). This means that for reasonable varieties of quark mass matrices which reproduce the CKM matrix, the up-quark mass matrix can be transformed to the Fritzsch form, while the down-quark mass matrix is kept in the NNI form. It is necessary to examine further the region of parameters of CKM matrix which allows this transformation.

(b) The case of the BS-type basis

Analysis can be done similarly to the Fritzsch case. We find

\[
\begin{align*}
(K^\dagger D^2_u K)_{11} & \simeq \sigma^2 m_t^2 , \\
(K^\dagger D^2_u K)_{22} & \simeq \rho^2 m_t^2 , \\
(K^\dagger D^2_u K)_{33} & \simeq m_t^2 , \\
(K^\dagger D^2_u K)_{12} & \simeq -\rho \sigma \sin \delta \, m_t^2 , \\
(K^\dagger D^2_u K)_{13} & \simeq \sigma \sin \delta \, m_t^2 , \\
(K^\dagger D^2_u K)_{23} & \simeq -\rho m_t^2 .
\end{align*}
\]  

(31)

Then, by using

\[
O_d \simeq \begin{pmatrix}
1 & -2^{-1/4}\sqrt{r_d} & 2^{-1/4}r_s\sqrt{r_d} \\
2^{-1/4}\sqrt{r_d} & 1 & r_s \\
2^{3/4}r_s\sqrt{r_d} & -r_s & 1
\end{pmatrix}
\]  

(32)

by keeping leading terms, we find that the condition is reduced to

\[
A'e^{i(\phi_{12}-\delta')}-iB'\sin \phi_{23} - C'e^{i(\phi_{12}-\delta'+\phi_{23})} = -D' ,
\]  

(33)

where \( \phi_{12} = \phi_1 - \phi_2 \), \( \phi_{23} = \phi_2 - \phi_3 \) and

\[
A' = \rho \sigma , \quad B' = 2^{3/4}r_s\sqrt{r_d} \rho , \quad C' = r_s \sigma' , \quad D' = 2^{-1/4}\sqrt{r_d}(\rho^2 - r_s^2) .
\]  

(34)
By taking the absolute values of both sides of the equation 
\[ e^{i(\phi_{12} - \delta')} \left( A' - C'e^{i(\phi_{23})} \right) = iB' \sin \phi_{23} - D' \], we obtain the equation for \( \phi_{23} \) as

\[ B'^2 \cos^2 \phi_{23} - 2A'C' \cos \phi_{23} + A'^2 + C'^2 - B'^2 - D'^2 = 0 \tag{35} \]

By using the values of quark masses and CKM elements given before and \( \sigma' \equiv |K_{td}| = 0.009[7] \), we obtain \( \cos \phi_{23} = -0.12 \). The phase \( \phi_{12} \) is determined once \( \phi_{23} \) is given. Although we did not take into account the experimental uncertainties in CKM elements, the above analysis suggests that for reasonable quark mass matrices, the condition will be satisfied. Therefore, it is possible that the down-quark mass matrix can be transformed into the BS form, while the up-quark mass matrix is kept in the NNI form in practice.

## 4 Summary

For three generation of quarks, there still remain two freedoms of the transformation of quark mass matrices which leave the CKM matrix invariant in the NNI basis. By utilizing these freedoms, we showed that either the Fritzsch-type or the BS-type basis is possible. Here the Fritzsch-type means that \( M_u \) takes the Fritzsch form, while \( M_d \) does the NNI form. On the other hand. The BS-type means that \( M_d \) takes the BS form, while \( M_u \) does the NNI form. We explicitly constructed these transformations and saw that the rephasing freedom of quarks plays an important role. Our work is an extension of Koide’s basis[5] where \( M_{u32} = 0 \) in the NNI basis.

The two bases, the Fritzsch-type and the BS-type as well as Koide’s basis contain only ten physical parameters in quark mass matrices so that quark mass matrices are expressed only by the observable, quark masses and CKM parameters. Both of our bases are symmetric type parameterizations contrary to Koide’s one which is asymmetric type.

It may be worthwhile to see the transformation between the Fritzsch-type and the BS-type bases which is explicitly given by

\[ \tilde{M}_u = (O_u P_u K P_d^l T_d^T) \tilde{M}_u (O_u V_u^T) \],
\[ \tilde{M}_{dB} = (O_d^T) \tilde{M}_d (O_d T_d) \]. \tag{36} \]
The transformations between Koide’s basis and our ones are similarly obtained, but we do not list here.

It is interesting to observe that the Fritzsch-BS ansatz where $M_u$ takes the Fritzsch form and $M_d$ does the BS form can be obtained from the BS basis by requiring the hermiticity for $M_u$. As discussed by Ito[4], the Fritzsch-BS ansatz may well be a good ansatz to explain the CKM matrix if the CP phase is in the first quadrant in the $\rho - \eta$ plane.

There are several works left. One is the examination on the region of CKM parameters which allows these transformations. The other is to express quark mass matrices by observable, quark masses and CKM parameters. These works will be reported in the forthcoming paper[8].
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