# Scalar mediated flavor changing neutral currents in a THDM within USY hypothesis

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**Abstract**

Scalar mediated flavor changing neutral currents (FCNC's) are investigated in a two Higgs doublet model (THDM) within universality of strength for Yukawa couplings (USY) hypothesis. They are inversely proportional to the vacuum expectation values (vev's) of the Higgs doublets and proportional to the magnitude of the Yukawa couplings $\lambda_Y$, and related to the Cabbibo-Kobayashi-Maskawa matrix $V_{CKM}$. In order to satisfy the experimental constraints of the neutral meson systems, some tuning is required for the model parameters to reduce sufficiently the contributions of the scalar mediated FCNC's. We discuss that the scalar mediated FCNC's may provide significant effects in the $B_s - \overline{B_s}$ mixing as New Physics (NP).

## 1. Introduction

We have been studied a THDM within USY hypothesis[1,2]. In this model, three ansatz are imposed as follows.

- Both Higgs doublets couple to the u-type quarks and the d-type quarks.
- The moduli of the Yukawa couplings are the same for the up-type quarks and the down-type quarks.
- The vev's of the two Higgs doublets take almost the same absolute values.

These ansatz provide some favorable features:

- The hierarchical relations for the quark masses, $m_b \ll m_t$ ,

$m_u, m_c \ll m_t, m_d$ and $m_s \ll m_b$, are naturally explained.

- The phase invariant CP violating parameter $J \equiv \mathrm{Im}(V_{im}V_{jn}V_{jm}^{*}V_{in}^{*})$ is obtained sufficiently.
- Scalar mediated flavor changing neutral currents (FCNC's) are present at the tree level.

In this study, the scalar mediated FCNC's for the d-type quarks are investigated. They are described with several parameters. Specifically, in order to satisfy the experimental constraints from neutral meson systems, some tuning is required among the vev's $v_1$ and $v_2$, the moduli of the Yukawa couplings $\lambda_Y$ and the associated phases of the Yukawa couplings.

This article is organized as follows. In Sec 2, the model and the scalar mediated FCNC's are described. In Sec 3, the experimental constraints are considered, and the possibility of NP is discussed. Sec 4 is devoted to summary.

## 2. Model and scalar mediated FCNC's

### 2-1. The model

Three specific ansatz are imposed in the THDM within USY hypothesis.

- Both Higgs doublets couple to the u-type quarks and the d-type quarks.
- The moduli of the Yukawa couplings are the same for up-type quarks and the down-type quarks.
- The vev's of the two Higgs doublets take almost the same absolute values.

Then the Yukawa couplings are given as

$$L_{Yukawa} = \lambda_Y \exp[i\theta_{uij}^{(1)}]\overline{q_{iL}}H_1 u_{jR} + \lambda_Y \exp[i\theta_{uij}^{(2)}]\overline{q_{iL}}H_2 u_{jR} + \lambda_Y \exp[i\theta_{dij}^{(1)}]\overline{q_{iL}}\phi\tilde{H}_1 d_{jR} + \lambda_Y \exp[i\theta_{dij}^{(2)}]\overline{q_{iL}}\tilde{H}_2 d_{jR} \tag{2.1}$$

where $q_{iL}=\begin{bmatrix} u_i \\ d_i \end{bmatrix}$. The neutral Yukawa couplings are specifically given as

$$L^{(u)}_{Yukawa(n)}=\frac{\lambda_Y}{\sqrt{2}}\lambda_Y\exp[i\theta^{(1)}_{uij}]\overline{u_{iL}}\phi_1 u_{jR}+\frac{\lambda_Y}{\sqrt{2}}\exp[i\theta^{(2)}_{uij}]\overline{u_{iL}}\phi_2 u_{jR}\text{, and}$$

$$L^{(d)}_{Yukawa(n)}=-\frac{\lambda_Y}{\sqrt{2}}\exp[i\theta^{(1)}_{dij}]\overline{d_{iL}}\phi_1 d_{jR}-\frac{\lambda_Y}{\sqrt{2}}\exp[i\theta^{(2)}_{dij}]\overline{d_{iL}}\phi_2 d_{jR}\,. \tag{2.2}$$

The two Higgs doublets are given as

$$H_1=\begin{bmatrix} H_1^+ \\ H_1^{0\prime} \end{bmatrix},\quad H_2=\begin{bmatrix} H_2^+ \\ H_2^{0\prime} \end{bmatrix}\ . \tag{2.3}$$

After the spontaneous symmetry breaking, they are described as

$$H_1=\begin{bmatrix} H_1^+ \\ \dfrac{v_1+H_1^0+i\chi_1^0}{\sqrt{2}} \end{bmatrix},\quad H_2=\begin{bmatrix} H_2^+ \\ \dfrac{v_2e^{i\delta'}+H_2^0+i\chi_2^0}{\sqrt{2}} \end{bmatrix} \tag{2.4}$$

where $\tan\beta\equiv\dfrac{v_2}{v_1}$.

The quark mass matrices are provided as

$$M_u=\frac{\lambda_Y v_1}{\sqrt{2}}\exp[i\theta^{(1)}_{uij}]+\frac{\lambda_Y v_2}{\sqrt{2}}\exp[i(\delta+\theta^{(2)}_{uij})],$$

$$M_d=\frac{\lambda_Y v_1}{\sqrt{2}}\exp[i\theta^{(1)}_{dij}]+\frac{\lambda_Y v_2}{\sqrt{2}}\exp[i(\delta+\theta^{(2)}_{dij})]\,. \tag{2.5}$$

Because of the hierarchical relations for the quark masses, $m_t\gg m_u,m_c$ and , $m_b\gg m_d,m_s$ we assume that $M_u$ and $M_d$ are almost in a democratic form as

$$M_u\simeq\frac{\lambda_Y(v_1+v_2e^{i\delta})}{\sqrt{2}}\begin{bmatrix}1&1&1\\1&1&1\\1&1&1\end{bmatrix}, \tag{2.6}$$

$$M_d\sim\frac{\lambda_Y(v_1e^{i\alpha_d}-v_2e^{i\beta_d'})}{\sqrt{2}}\begin{bmatrix}1&1&1\\1&1&1\\1&1&1\end{bmatrix}. \tag{2.7}$$

The center of perturbative calculation for the d-type quark masses is particularly given with the angles $\alpha_d$ and $\beta_d'$ as shown in Fig.1.

$$\cos\alpha_d = \frac{3}{2m_b v_1}\cdot\frac{\sqrt{2}}{\lambda_Y}\left[\left(\frac{\lambda_Y}{\sqrt{2}}\right)^2 (v_1^2 - v_2^2) + \frac{m_b{}^2}{9}\right],$$

$$\cos\beta_d' = \frac{3}{2m_b v_2}\cdot\frac{\sqrt{2}}{\lambda_Y}\left[\left(\frac{\lambda_Y}{\sqrt{2}}\right)^2 (v_1^2 - v_2^2) - \frac{m_b{}^2}{9}\right],$$

$$\sin\alpha_d = \frac{3}{2m_b v_1}\cdot\frac{\sqrt{2}}{\lambda_Y}\sqrt{\frac{m_b{}^2\lambda_Y^2}{9}(v_1^2 + v_2^2) - \left(\frac{\lambda_Y}{\sqrt{2}}\right)^4 (v_1^2 - v_2^2) - \frac{m_b{}^2}{9}},$$

$$\sin\beta_d' = \frac{3}{2m_b v_2}\cdot\frac{\sqrt{2}}{\lambda_Y}\sqrt{\frac{m_b{}^2\lambda_Y^2}{9}(v_1^2 + v_2^2) - \left(\frac{\lambda_Y}{\sqrt{2}}\right)^4 (v_1^2 - v_2^2) - \frac{m_b{}^2}{9}}. \qquad (2.8)$$

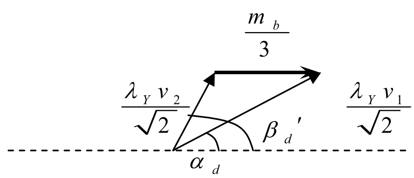


Fig. 1. The center of perturbative calculation.

Then the USY phases are determined as [2]

$$\theta_{dij}^{(1)\prime} = \frac{\sqrt{2}m_b}{3v_1\lambda_Y}\cdot\frac{(P_{ij}\cos\beta_d' + Q_{ij}\sin\beta_d')}{\sin(\alpha_d - \beta_d')} \quad (\theta_{dij}^{(1)} = \alpha_d + \theta_{dij}^{(1)\prime}), \qquad (2.9)$$

$$\theta_{dij}^{(2)\prime} = -\frac{\sqrt{2}m_b}{3v_2\lambda_Y}\cdot\frac{(P_{ij}\cos\alpha_d + Q_{ij}\sin\alpha_d)}{\sin(\alpha_d - \beta_d')} \quad (\theta_{dij}^{(2)} = \beta_d' + \theta_{dij}^{(2)\prime}).$$

## 2-2. Scalar mediated FCNC's

We concentrate on the Yukawa couplings of the d-type quarks in the following. The mass matrix, $M_d$, is diagonalized as

$$V_{dL} M_d V_{dL}^\dagger = \begin{bmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{bmatrix}, \qquad (2.10)$$

where $V_{dL}$ is unitary matrix as

$$V_{dL} = V_{CKM}^\dagger V_u \simeq V_{CKM}^\dagger F_u , \qquad (2.11)$$

$V_{uL}$ is another unitary matrix to diagonalize $M_u$ , and $F_u$ is an orthogonal matrix composed of the three eigenvectors of the democratic matrix [2]. The Yukawa couplings of the d-type quarks with the scalar $\phi_1$ are given as

$$\begin{aligned}
\Lambda_{dij}^{(1)} &= \frac{\lambda_Y}{\sqrt{2}} V_{dL} e^{i\alpha_d} \cdot e^{i\theta_{dij}^{(1),}} V_{dL}^\dagger \\
&= \frac{\lambda_Y}{\sqrt{2}} e^{i\alpha_d} V_{dL} \left[ e^{i\theta_{dij}^{(1)\prime}} \left\{ \left( 1 + i\gamma_{ij}^{(1)\prime} \right) - i\gamma_{ij}^{(1)\prime} \right\} \right] V_{dL}^\dagger \\
&= \frac{\lambda_Y}{\sqrt{2}} e^{i\alpha_d} V_{dL} \left[ e^{i\theta_{dij}^{(1)\prime}} \cdot e^{i\gamma_{ij}^{(1),}} \right] V_{dL}^\dagger - i \frac{\lambda_Y}{\sqrt{2}} e^{i\alpha_d} V_{dL} \left[ e^{i\theta_{dij}^{(1)\prime}} \cdot \gamma_{ij}^{(1),} \right] V_{dL}^\dagger . \qquad (2.12)
\end{aligned}$$

The first term is diagonalized together with $M_d$ , without generating FCNC's. On the other hand, the second term generally provide scalar mediated FCNC's at the tree level. It is calculated as

$$\begin{aligned}
\Lambda_{dij}^{(1)\prime} &= -i \cdot \frac{3\lambda_Y e^{i(\alpha_d + \beta_d')}}{\sqrt{2} v_1 \sin(\alpha_d - \beta_d')} V_{dL} e^{i\theta^{(1)\prime}} P_{ij} V_{dL}^\dagger \\
&\simeq -i \cdot \frac{3\lambda_Y e^{i(\alpha_d + \beta_d')}}{\sqrt{2} v_1 \sin(\alpha_d - \beta_d')} V_{dL} ( \quad 1 \quad + i\theta^{(1)'} ) P_{ij} V_{dL}^\dagger \\
&\simeq -i \cdot \frac{3\lambda_Y e^{i(\alpha_d + \beta_d')}}{\sqrt{2} v_1 \sin(\alpha_d - \beta_d')} V_{dL} P_{ij} V_{dL}^\dagger \\
&\simeq -i \cdot \frac{3\lambda_Y e^{i(\alpha_d + \beta_d')}}{\sqrt{2} v_1 \sin(\alpha_d - \beta_d')} \times (-3) \begin{bmatrix} * & -ny & n \\ -ny & * & -y \\ n & -y & * \end{bmatrix} \\
&\simeq -i \cdot \frac{3\lambda_Y e^{i(\alpha_d + \beta_d')}}{\sqrt{2} v_1 \sin(\alpha_d - \beta_d')} \begin{bmatrix} 0.0034 & 0.0009 + 0.0004i & -0.0226 + 0.000006i \\ 0.0009 - 0.0004i & 0.0628 & 0.1247 - 0.00005i \\ -0.0226 - 0.000006i & 0.1247 + 0.00005i & 0.0107 \end{bmatrix}
\end{aligned}$$

(2.13)

where $P_{ij}$ is a 3×3 Hermitian matrix, which is explicitly presented in [2], and $n$, $y$ are the elements of $V_{CKM}$ as

$$V_{CKM} \simeq \begin{bmatrix} \cos\theta_C & \sin\theta_C & m-ix \\ -\sin\theta_C & \cos\theta_C & y \\ n-ix & -y & 1 \end{bmatrix} . \tag{2.14}$$

The Yukawa couplings with the scalar $\phi_2$ are also calculated as

$$\begin{aligned} \Lambda_{dij}^{(2)\prime} &= i \cdot \frac{3\lambda_Y e^{i(\alpha_d+\beta_d'-\delta)}}{\sqrt{2}v_2 \sin(\alpha_d-\beta_d')} V_{dL} e^{i\theta^{(2)\prime}} P_{ij} V_{dL}^{\dagger} \\ &\simeq i \cdot \frac{3\lambda_Y e^{i(\alpha_d+\beta_d'-\delta)}}{\sqrt{2}v_2 \sin(\alpha_d-\beta_d')} V_{dL} ( \quad 1 \quad + i\theta^{(2)'} ) P_{ij} V_{dL}^{\dagger} \\ &\simeq i \cdot \frac{3\lambda_Y e^{i(\alpha_d+\beta_d'-\delta)}}{\sqrt{2}v_2 \sin(\alpha_d-\beta_d')} V_{dL} P_{ij} V_{dL}^{\dagger} \\ &\simeq i \cdot \frac{3\lambda_Y e^{i(\alpha_d+\beta_d'-\delta)}}{\sqrt{2}v_2 \sin(\alpha_d-\beta_d')} \times (-3) \begin{bmatrix} * & -ny & n \\ -ny & * & -y \\ n & -y & * \end{bmatrix} \\ &\simeq i \cdot \frac{3\lambda_Y e^{i(\alpha_d+\beta_d'-\delta)}}{\sqrt{2}v_2 \sin(\alpha_d-\beta_d')} \begin{bmatrix} 0.0034 & 0.0009+0.0004i & -0.0226+0.000006i \\ 0.0009-0.0004i & 0.0628 & 0.1247-0.00005i \\ -0.0226-0.000006i & 0.1247+0.00005i & 0.0107 \end{bmatrix} \end{aligned} \tag{2.15}$$

It turns out that the scalar mediated FCNC's are inversely proportional to $v_1$ or $v_2$ and proportional to $\lambda_Y$. Moreover they are related to the elements of $V_{CKM}$ as

$$\Lambda_{d12}^{(a)\prime},\ \Lambda_{d21}^{(a)\prime} \propto ny \sim |V_{td}||V_{ts}|,$$

$$\Lambda_{d13}^{(a)\prime},\ \Lambda_{d31}^{(a)\prime} \propto n \sim |V_{td}|,$$

$$\Lambda_{d23}^{(a)\prime},\ \Lambda_{d23}^{(a)\prime} \propto y \sim |V_{ts}|, \tag{2.16}$$

where it follows from the experimental data on $V_{CKM}$ that

$$|V_{td}||V_{ts}| \ll |V_{td}| < |V_{ts}| . \tag{2.17}$$

Then the generation hierarchy of the FCNC's is automatically explained. The scalar mediated FCNC's between the first and second generations are strongly suppressed. On the other hand, those between the second and third generations are not suppressed stringently. Hence New Physics may be discovered in the $B_s$ neutral meson experiments.

## 3. Experimental constraints and possibility of NP

### 3-1. Experimental constraints

We discuss the experimental constraints on the scalar mediated FCNC's [3].

#### 3-1-1. $\Delta m_K, \varepsilon$

We first consider the experimental constraints on the $K^0 - \overline{K^0}$ mixing. There is no FCNC at the tree level in the standard model (SM). Then the FCNC is dominantly induced by a box diagram with the intermediate charged W boson (Fig.2). It is suppressed by the GIM mechanism.

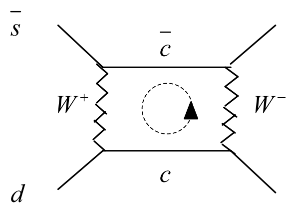


Fig. 2. W boson mediated box diagram in the $K^0 - \overline{K^0}$ mixing.

In this model there are also the neutral scalar mediated FCNC's at the tree level (Fig.3).

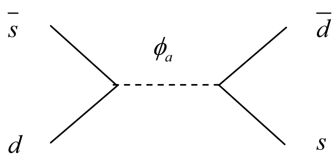


Fig. 3. Scalar mediated tree diagram in the $K^0 - \overline{K^0}$ mixing.

The state of mixture between $K^0$ and $\overline{K^0}$ is expressed as $\alpha|K^0\rangle + \beta|\overline{K^0}\rangle$. Its time development is governed by the Schrodinger equation,

$$i\frac{d}{dt}\begin{pmatrix}\alpha\\ \beta\end{pmatrix}=H_{eff}\begin{pmatrix}\alpha\\ \beta\end{pmatrix},\tag{3.1}$$

where $H_{eff}$ is the effective Hamiltonian given as

$$H_{eff}=\left(\mathbf{M}-\frac{i}{2}\mathbf{\Gamma}\right)\equiv\begin{pmatrix}M_{11} & M_{12}\\ M_{21} & M_{22}\end{pmatrix}-\frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12}\\ \Gamma_{21} & \Gamma_{22}\end{pmatrix}.\tag{3.2}$$

In SM the $K^0-\overline{K^0}$ mixing is dominantly caused in the box diagram mediated by the charged W boson. In this model, it may also be caused in the tree diagram mediated by the neutral scalars. The effective Hamiltonian provided by the scalar mediated tree diagrams are written with the four-component Dirac fields as

$$H_\phi^{\Delta S=2}=\sum_{a=1,2}\frac{1}{m_{\phi_a}^2}\left[\bar{s}\left\{\left(\Gamma_a^S\right)_{12}+\left(\Gamma_a^P\right)_{21}\gamma_5\right\}d\right]^2,\tag{3.3}$$

where

$$\left(\Gamma_a^S\right)_{12}=\frac{1}{2}\left[\left(\Lambda_{12}^{(a)\prime}\right)^*+\left(\Lambda_{21}^{(a)\prime}\right)\right],\ \left(\Gamma_a^P\right)_{12}=\frac{1}{2}\left[\left(\Lambda_{12}^{(a)\prime}\right)^*-\left(\Lambda_{21}^{(a)\prime}\right)\right].\tag{3.4}$$

Then, the $K^0-\overline{K^0}$ transition matrix element is calculated with the effective Hamiltonian as

$$\begin{aligned}M_{12}(\phi_a)&=\left\langle\overline{K}^0\middle|H_\phi^{\Delta S=2}\middle|K^0\right\rangle\\&=\sum_{a=1,2}\frac{1}{6m_{\phi_a}^2}\left[\left\{\left(\Gamma_a^S\right)_{12}^2-\left(\Gamma_a^P\right)_{21}^2\right\}M_A^0+\left\{-\left(\Gamma_a^S\right)_{21}^2+11\left(\Gamma_a^P\right)_{21}^2\right\}M_P^0\right],\end{aligned}\tag{3.5}$$

where

$$M_A^0=f_K^2m_K^2,\quad M_P^0=\frac{f_K^2m_K^4}{(m_d+m_s)}.\tag{3.6}$$

The mass difference $\Delta m_K$ is given by the transition amplitude as

$$\Delta m_K=\left|\frac{1}{m_K}M_{12}\right|.\tag{3.7}$$

By using the vacuum insertion approximation, the neutral Higgs scalar contribution to the neutral $K$ meson mass difference is given as

$$\Delta m_K(\phi_a) = \left| \frac{1}{m_b} \left\langle \overline{K}^0 \left| H_\phi^{\Delta S=2} \right| K^0 \right\rangle \right|. \tag{3.8}$$

The CP asymmetry parameter $\varepsilon$ is also given as

$$\varepsilon = \frac{\operatorname{Im} M_{12}}{\operatorname{Re} M_{12}} \tag{3.9}$$

The experimental values of these quantities [4] are given as

$$\Delta m_K = 3.5 \times 10^{-15}\,\text{GeV}, \tag{3.10}$$

$$|\varepsilon| = 2.3 \times 10^{-3}. \tag{3.11}$$

By using the coupling matrices $\Lambda_{ij}^{(a)\prime}$ in (2.13) and (2.15), the transition amplitude is estimated perturbatively as

$$\operatorname{Re} M_{12}(\phi_a) = M_{12}(\phi_a) \sim \frac{{\lambda_Y}^2}{m_{\phi_a}^2 v^2 \sin(\alpha_d - \beta_d')} \times 10^{-7} \sim \frac{{\lambda_Y}^4}{m_{\phi_a}^2 v^2} \times 10^{-3}, \tag{3.12}$$

$$\operatorname{Im} M_{12}(\phi_a) = \alpha_K M_{12}(\phi_a), \tag{3.13}$$

$$(\because 1/\sin(\alpha_d - \beta_d') \sim 100\lambda_Y)$$

where $\alpha_K$ is a CP violating parameter from the neutral scalar mediated FCNC's. The contributions of the neutral scalar diagrams should not exceed the experimental values as

$$\Delta m_K(\phi_a) = \left| \frac{1}{m_K} M_{12}(\phi_a) \right| < 3.5 \times 10^{-15}\,\text{GeV} \tag{3.14}$$

$$|\varepsilon(\phi_a)| = \left| \frac{\operatorname{Im} M_{12}(\phi_a)}{\operatorname{Re} M_{12}(\phi_a)} \right| < 2.3 \times 10^{-3}. \tag{3.15}$$

From the experimental values of $m_Z$, $m_{\phi_a}$, $m_t$, constraints for the parameters are placed as

$$\lambda_Y > 0.23\,,\quad v_1 \simeq v_2 \simeq v \simeq 180\,,\quad m_{\phi_a} \sim 120 \tag{3.16}$$

Then, the scalar effect for $\Delta m_K$ is estimated with (3.12) as

$$\Delta m_K(\phi_a) > 6\times 10^{-15}\,\text{GeV}, \tag{3.17}$$

where possible cancellation between the contributions of the two scalar diagrams is not considered. Since this estimate apparently exceeds the experimental value (3.10), some tuning is required for the scalar mediated FCNC's. Furthermore, in order to reproduce the small CP violation parameter as given in (3.11), $\Lambda_{ij}^{(a)\prime}$ are assumed to be almost Hermitian.

3-1-2. $\Delta m_B$

We next consider the experimental constraint on the $B^0-\overline{B^0}$ mixing. The experimental value of the mass difference [4] is given as

$$\Delta m_B = 3.1\times 10^{-13}\ \ \text{GeV}. \tag{3.18}$$

Similarly to the $K^0-\overline{K^0}$ mixing, the transition amplitude generated by a neutral scalar mediated tree diagram (Fig.4) is perturbatively calculated as

$$M_{12}(\phi_a) \sim 3\times\frac{\lambda_Y{}^4}{m_{\phi_a}^2 v^2}\,. \tag{3.19}$$

Then the scalar effect for $\Delta m_B$ is estimated naively as

$$\Delta m_B(\phi_a) > 4\times 10^{-12}\,\text{GeV}. \tag{3.20}$$

Since this exceeds slightly the experimental value (3.18), some tuning is required for the scalar mediated FCNC's.

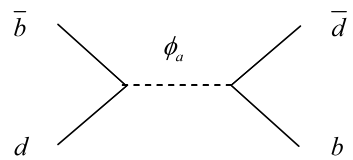


Fig. 4. Scalar mediated tree diagram in the $B^0-\overline{B^0}$ mixing.

3-1-3. $\Delta m_{B_s}$

We further consider the experimental constraint on the $B_s^0 - \overline{B_s^0}$ mixing. The experimental value of the mass difference [4] is given as

$$\Delta m_{B_s} = 1\times 10^{-11}\ \text{GeV}. \tag{3.21}$$

The transition amplitude generated by a neutral scalar mediated tree diagram (Fig.5) is perturbatively calculated as

$$M_{12}(\phi_a) \sim 100\times \frac{\lambda_Y{}^4}{m_{\phi_a}^2 v^2}. \tag{3.22}$$

Then the scalar effect for $\Delta m_{B_s}$ is estimated as

$$\Delta m_{B_s}(\phi_a) > 1\times 10^{-10}\,\text{GeV}. \tag{3.23}$$

Since this exceeds the experimental value (3.18), some tuning is required for the scalar mediated FCNC's.

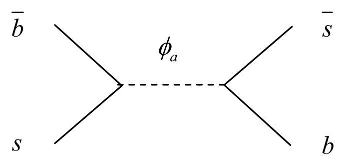


Fig. 5. Scalar mediated tree diagram in the $B_s^0 - \overline{B_s^0}$ mixing.

3-1-4. $\varepsilon'/\varepsilon$

We here discus the direct CP violation parameter $\varepsilon'/\varepsilon$ in the $K^0, \overline{K^0} \to 2\pi$ decays. In order to calculate $\varepsilon'/\varepsilon$, we introduce a parameter

$$\xi \equiv \frac{\text{Im}\left\langle 2\pi(I=0\left|H_{eff}^{\Delta S=1}\right|K^0\right\rangle}{\text{Re}\left\langle 2\pi(I=0\left|H_{eff}^{\Delta S=1}\right|K^0\right\rangle}\ . \tag{3.24}$$

In SM the decays are dominated by a penguin diagram mediated by the charged W boson (Fig.6). In this model there is also a contribution by a penguin diagram mediated by the neutral scalar (Fig.7).

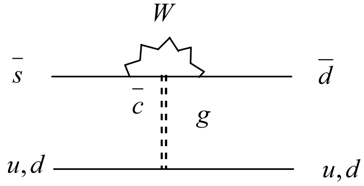


Fig. 6. W boson mediated penguin diagram in the $K^0, \overline{K^0} \to 2\pi$ decays.

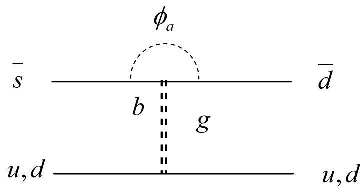


Fig. 7. Scalar mediated penguin diagram in the $K^0, \overline{K^0} \to 2\pi$ decays.

Since the d-type quark masses are much smaller than that of the W boson, the FCNC's by the neutral scalars are suppressed. The W penguin mainly contributes to the real component of the decay amplitude. On the other hand, the neutral scalar penguin contribution can be large for the imaginary component, which is calculated as

$$\xi(\phi) \sim \frac{1}{16 m_g^2 G_F \sin\theta_C \cos\theta_C \ln(m_c^2/m_K^2)} \times \frac{m_s(f_K + f_\pi + f_K m_K^2/m_\sigma^2)}{f_K - f_\pi + f_K m_K^2/m_\sigma^2} \times \mathrm{Im}\left(\Lambda_{13}^{(a)\prime}\Lambda_{32}^{(a)\prime}\right) \cdot \frac{m_b}{m_{\phi_a}^2} \cdot I(m_b^2/m_\phi^2), \tag{3.25}$$

with

$$I(X) = \frac{1}{(1-X)^2}\left(-\frac{3}{2} + \frac{1}{2}X - \frac{2}{1-X}\ln X\right). \tag{3.26}$$

For $m_{\phi_a} \sim 120$ GeV, we obtain $I(m_b^2/m_{\phi_a}^2) \sim 12$. By using (2.13) for the scalar mediated FCNC's $\Lambda_{ij}^{(a)\prime}$, which are assumed to be almost Hermitian, we estimate $\xi$ as

$$\xi(\phi) \sim \frac{9\lambda_Y^4}{v^2} \times 10^{-2} \geq 8 \times 10^{-10} . \tag{3.27}$$

The direct CP violation parameter $\varepsilon'/\varepsilon$ is related to $\xi$ as

$$\varepsilon'/\varepsilon = -\frac{1}{20}\left(\frac{2\xi}{\varepsilon_m + 2\xi}\right) \simeq -\frac{1}{10}\left(\frac{\xi}{\varepsilon}\right), \tag{3.28}$$

Then, the effect of scalar mediated diagram is given as

$$\varepsilon'(\phi)/\varepsilon \geq 3 \times 10^{-8}, \tag{3.29}$$

while experimentally

$$\varepsilon'/\varepsilon = (1.5 \pm 0.8) \times 10^{-3} . \tag{3.30}$$

Hence there is a relatively large parameter space to reproduce this experimental value.

## 3-2. Possibility of New Physics

We now discuss the possibility of NP. In this paper we have required some tunings between the two scalar mediated tree diagrams for the neutral meson mixings to reproduce the experimental data of $K^0 - \overline{K^0}$ , $B^0 - \overline{B^0}$ , $B_s^0 - \overline{B_s^0}$ . We have also assumed that the scalar mediated FCNC's are almost Hermitian to reproduce the small direct CP violation parameter $\varepsilon'/\varepsilon$. Under this realistic situation, there is a good chance for the scalar mediated FCNC's to serve as NP especially in future experiments of $B_s^0$ meson.

## 4. Summary

We have investigated the scalar mediated FCNC's in a THDM within USY hypothesis. They are inversely proportional to the vev's of the two Higgs doublets and proportional to the magnitude of the Yukawa couplings $\lambda_Y$. Moreover they are related to the elements of Cabbibo-Kobayashi-Maskawa matrix $V_{CKM}$ so that the flavor hierarchy of the FCNC's is automatically explained.

The effects of the scalar mediated FCNC's for the neutral meson mixings are perturbatively evaluated. The results appear to exceed the experimental data, so that some tunings are required between the two diagrams mediated by $\phi_1$ and $\phi_2$. Given these tunings reasonably, there is a good chance for the scalar mediated FCNC's to serve as NP especially in future experiments of $B_s^0$ meson.

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