Flavor Changing Neutral Processes Bounded By $B_d^0 - \overline{B}_d^0$ Mixing and Predictions for the Tau-Charm Factory

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I. INTRODUCTION

In our present understanding of particle physics, there is one potentially important piece of experimental data whose explanation may require new physics beyond the standard model. It is the surprisingly large B_d^0 - $\bar{B}_d^0$ mixing reported by the ARGUS[1] collaboration, which has been confirmed by the CLEO[2] collaboration.

In this talk, we propose that this mixing is due to or is a bound to tree-level flavor changing couplings of the standard model Higgs scalar, H^0, or the Z^0, induced by new physics beyond the standard model. A more complete treatment of this by these authors is in Refs. 3 and 4. In Sec. 2, we present an illustrative example, based on new heavy weak-isospin singlet heavy quarks, where physics beyond the standard model could be responsible for such flavor changing neutral current processes (FCNP) of the known quarks and leptons. In Sec. 3, we look at various theoretical expectations for the flavor dependence of these couplings. In Sec. 4, we assume that the large $B_d^0 - \bar{B}_d^0$ mixing is due to such FCNP and this anchors one of these couplings. We then analyze all relevant processes using the assumptions on the dependence of the couplings on quark or lepton masses from Sec. 3. The results are pleasing in that not only are the bounds not seriously violated, but several unseen reactions are on the verge of observability. In this talk we focus on those that are relevant for the τ-charm factory.

We summarize here the main results for the τ-charm factory. If the observed $B_d^0 - \bar{B}_d^0$ mixing is due to the flavor changing coupling of H^0, the key predictions are $r_D(D^0 - \bar{D}^0$ mixing) of order 2×10^{-3} which is larger than the standard model and can be observed at the τ-charm factory. It also predicts $BR(\mu^- \to e^- \gamma) \simeq 1 \times 10^{-12}$, and the mass of the Higgs scalar $M_H \simeq (200 - 300)$ GeV.

In case the observed $B_d^0 - \bar{B}_d^0$ mixing is due to the flavor changing coupling of Z^0, the rare decay mode $\mu^- \to e^- e^+ e^-$ is predicted to be observable at any time in the near future with the branching ratio in the neighborhood of the present experimental upper limit, while other predictions include: $r_D(D^0 - \bar{D}^0$ mixing) of order 1×10^{-3}, and $BR(\tau^- \rightarrow \mu^-\mu^+\mu^-) \simeq 1 \times 10^{-7}$ (which is at the edge of observability in the τ-charm facility). This case also predicts large branching ratios for flavor changing decay modes of the Z^0 to a heavy top quark or fourth generation quarks or leptons: the $BR(Z^0 \rightarrow t\bar{c} + c\bar{t})$, $BR(Z^0 \rightarrow b'\bar{b} + b\bar{b}')$, and $BR(Z^0 \rightarrow \tau'\bar{\tau} + \bar{\tau}'\tau)$, are in the range of yielding 1,000 to 5,000 events for 10^7 Z^0 produced at LEP. In this case, from the observed strength of $B^0_d - \bar{B}^0_d$ mixing, the scale of new physics can be inferred to be $M \simeq 250$ GeV.

II. AN ILLUSTRATIVE EXAMPLE: VECTOR SINGLET MODEL

As a simple, illustrative example of the general class of models, in which tree-level neutral flavor changing couplings of H^0 and Z^0 between ordinary quarks and leptons are generated through the effect of mixings with heavy exotic fermions, we consider a model with an $SU(2)_L$ vector singlet of charge $-1/3$ quarks, D^0_L and D^0_R, plus the three standard initial down quarks $\tilde{d}^0_l$ as $SU(2)_L$ doublets and $\tilde{d}^0_R$ as singlets.[5]

The new $SU(2)_L$ vector singlets D^0_L and D^0_R being singlets are allowed a mass term without coupling to the Higgs $SU(2)_L$ doublet, and there is also a mixing term of $\tilde{d}^0_L$ and D^0_R coupling to the neutral Higgs field ϕ:

$$-L_Y = \overline{\tilde{d}^0_L}[\tilde{y}]\tilde{d}^0_R\phi/\sqrt{2} + \overline{\tilde{d}^0_L}[\tilde{Y}]D^0_R\phi/\sqrt{2} + \overline{D^0_L}D^0_R \tag{2.1}$$

where $[\tilde{Y}]$ is a 3-dimensional column vector and $[\tilde{y}]$ is a 3×3 matrix.

The basic three $SU(2)_L$ doublet quarks are then joined with the new massive D^0_L to make a four component down quark system that can mix:

$$d^0_L = \begin{pmatrix} \tilde{d}^0_L \\ D^0_L \end{pmatrix}, \qquad d^0_R = \begin{pmatrix} \tilde{d}^0_R \\ D^0_R \end{pmatrix} \tag{2.2}$$

The 3×3 matrix $[\tilde{y}]$ makes up the first three row and columns of the 4×4 Yukawa coupling matrix, and $[\tilde{Y}]$ makes up three elements of the fourth column to yield:

$$(y^d) = \begin{bmatrix} y_{11} & y_{12} & y_{13} & y_{14} \\ y_{21} & y_{22} & y_{23} & y_{24} \\ y_{31} & y_{32} & y_{33} & y_{34} \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{2.3}$$

The neutral Higgs field gets a vacuum expectation value v with a physical Higgs H^0: $\phi = v + H^0$. In the basis of weak-eigenstates d^0_{iL} and d^0_{jR}, the mass and the Yukawa couplings of the charge $-1/3$ quarks are given by

$$-L_Y = \overline{d^0_L}(M^d)d^0_R + \overline{d^0_L}(y^d)d^0_R H^0/\sqrt{2} + \text{h.c.} \tag{2.4}$$

where

$$(M^d) = (y^d)v/\sqrt{2} + (M'), \qquad v \equiv (\sqrt{2}G_F)^{-1/2} = 246 \quad \text{GeV} \tag{2.5}$$

with

$$(M') = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & M \end{bmatrix}. \tag{2.6}$$

In Eqs. (2.3) and (2.6), $i, j = 1, 2, 3$ correspond to the three families of ordinary d-type quarks (d, s, b), while $i, j = 4$ corresponds to the heavy exotic ones, D_L and D_R. (M') of Eq. (2.6) is due to the bare mass term M and takes the given form without any loss of generality.

The mass matrix (M^d) can be diagonalized by the unitary matrices V_L and V_R,

$$(V_L)^\dagger (M^d)(V_R) \equiv M^d_{diag.}. \tag{2.7}$$

The important point is that from Eq.(2.5), diagonalizing (M^d) does not completely diagonalize the Yukawa couplings, which are proportional to (y^d), because of the extra term (M'), which results in neutral flavor changing mixings in the Higgs couplings. Defining the mass-eigenstates d_L and d_R by

$$d^0_L \equiv (V_L)d_L, \qquad d_L \equiv (V_L^\dagger)d^0_L \tag{2.8}$$

$$d^0_R \equiv (V_R)d_R, \qquad d_R \equiv (V_R^\dagger)d^0_R, \tag{2.9}$$

the Yukawa couplings of the (standard model) Higgs scalar H^0 are given by

$$-L_Y^{H^0} = \overline{d_L}[(V_L^\dagger)(y^d)(V_R)]d_R H^0/\sqrt{2} + \text{h.c.} \tag{2.10}$$

$$= \overline{d_{iL}}(M^d_{diag.})_{ii} d_{iR} H^0/v - (M/v)\overline{d_{iL}}(V_L)^*_{4i}(V_R)_{4j} d_{jR} H^0 + \text{h.c.} \tag{2.11}$$

where we have used $(y^d) = \{(M^d) - (M')\}(\sqrt{2}/v)$, from Eq. (2.5). Thus the flavor changing coupling of H^0 is given by

$$L^{H^0}_{\text{F.C.}} = y'_{ij}\overline{d_{iL}} d_{jR} H^0 + \text{h.c.} \qquad \text{for} \qquad i \neq j \tag{2.12}$$

where

$$y'_{ij} = (M/v)(V_L)^*_{4i}(V_R)_{4j} \qquad \text{for} \qquad i \neq j \tag{2.13}$$

In the basis of weak-eigenstates, the neutral current coupling of Z^0 is

$$L^{Z^0}_{\text{N.C.}} = (e/\sin\theta_W\cos\theta_W)J^0_\mu Z^\mu \tag{2.14}$$

where

$$J^0_\mu = J^3_\mu - \sin^2\theta_W J^{\text{em}}_\mu \tag{2.15}$$

$$= \overline{d^0_{iL}}(t^L_3)_{ii}\gamma_\mu d^0_{iL} - (-1/3)\sin^2\theta_W[\overline{d^0_{iL}}\gamma_\mu d^0_{iL} + \overline{d^0_{iR}}\gamma_\mu d^0_{iR}] \tag{2.16}$$

$$(t^L_3) = \text{diag.}(-1/2,-1/2,-1/2,0) = (-1/2)[\text{diag.}(1,1,1,1) - \text{diag.}(0,0,0,1)] \tag{2.17}$$

In terms of the mass-eigenstates of Eq. (2.7) , Eq. (2.16) becomes

$$J^0_\mu = (-1/2)\overline{d_{iL}}\gamma_\mu d_{iL} + (1/2)\overline{d_{iL}}(V_L)^*_{4i}(V_L)_{4j}d_{jL} - (-1/3)\sin^2\theta_W[\overline{d_{iL}}\gamma_\mu d_{iL} + \overline{d_{iR}}\gamma_\mu d_{iR}] \tag{2.18}$$

Thus, the flavor changing couplings of the Z^0 are

$$L^{Z^0}_{\text{F.C.}} = (e/2\sin\theta_W\cos\theta_W)\hat{g}^L_{ij}\overline{d_{iL}}\gamma^\mu d_{jL}Z^0_\mu \qquad \text{for} \qquad i \neq j \tag{2.19}$$

with

$$\hat{g}^L_{ij} = (V_L)^*_{4i}(V_L)_{4j} \qquad \text{for} \qquad i \neq j. \tag{2.20}$$

The main results of this section show that the flavor changing couplings of H^0 and Z^0 are given by Eqs. (2.12), (2.13), (2.19), and (2.20), with strengths proportional to the product of the mixing angles $(V_L)^*_{4i}$ and $(V_{L,R})_{4j}$ of the unitary matrices V_L and V_R. We note that the Z^0 flavor changing couplings, Eq. (2.20) are just mixing angles, while the H^0 couplings, Eq. (2.13) also contain the new heavy quark mass scale in the ratio M/v.

III. THEORETICAL EXPECTATIONS ON THE FLAVOR DEPENDENCE OF THE FLAVOR CHANGING COUPLINGS

In Sec. 2, Eq. (2.13) and Eq. (2.20), we have seen that, in the context of a simple vector singlet model, the flavor changing couplings are proportional to the product of mixing angles $(V_{L,R})^*_{4i}(V_{L,R})_{4j}$. We expect similar results to hold in other models involving heavy exotic fermions. In this section, we consider how such mixing angles ($(V_{L,R})_{4j}$'s) should depend on the generation (family) index j. From experience with KM angles, we expect

$$|(V_{L,R})_{41}| \ll |(V_{L,R})_{42}| \ll |(V_{L,R})_{43}| \ll 1. \tag{3.1}$$

Lighter fermions are expected to have smaller mixing with the heavy exotic ones in order to keep their masses small; too much mixing would spoil this smallness. This may be the reason why the flavor changing neutral processes between the first two lightest families(i.e., $d \leftrightarrow s$, $e \leftrightarrow \mu$) have not been observed thus far, and the GIM[6] mechanism has been so successful, since these are the ones that are likely to be the most suppressed in terms of the mixing angles.

From the above discussion on the mixing angles and the mass ratios, and a simple model for mixing in Ref. (3), we take a standard assumption for the mass dependence of $(V_{L,R})_{4j}$ as

$$(V_{L,R})_{4j} \simeq \sqrt{\frac{m_j}{M}} \tag{3.2}$$

In Ref. (3) we also investigated a stronger variation with mass, and found it to lead to inconsistencies. For Higgs exchange, using the above result we have for y'_{ij}

$$y'_{ij} \simeq \frac{\sqrt{m_i m_j}}{v}. \tag{3.3}$$

For Z^0 exchange, we have

$$\hat{g}_{ij} \simeq \frac{\sqrt{m_i m_j}}{M} \tag{3.4}$$

IV. COMPARISON WITH EXISTING DATA AND PREDICTIONS FOR FUTURE EXPERIMENTS

The largest flavor changing neutral current couplings will then be for t and b quarks, and for τ leptons. It thus makes sense that we should set bounds from a possible FCNP involving the b quarks, namely $B^0_d - \bar{B}^0_d$ mixing. In $B^0_d - \bar{B}^0_d$ mixing, the b and $\bar{d}$ annihilate in a FCNP to a H^0 or Z^0 and reappear as a $b - \bar{d}$ in a tree level diagram. There is also a crossed graph for $b \to d$ and $\bar{d} \to \bar{b}$ with an H^0 or Z^0 exchange. Although $B^0_d - \bar{B}^0_d$ mixing occurs at a large level, it is still a better or comparable bound to the very stringent ones involving the lighter quarks, since they are expected to have much smaller FCNC couplings. A similar situation would apply for τ leptons or c quarks as observable at a tau-charm factory.

We have investigated a variety of FCNP which are likely to provide the most stringent constraints on the flavor changing couplings of H^0 and Z^0; the details are published in Ref.[3] and summarized in the first three columns of Table 1 and Table 2 of that reference. In that reference, the results for $B^0_d - \bar{B}^0_d$ mixing are not to be taken as a bound, but as a positive result fixing the parameters coupling the b-quark to the d-quark.

Considering $B_d^0 - \bar{B}_d^0$ mixing as an anchor for the FCNP, we use the results of the last section to predict the expected values for other coupling constants and compare these with experimental data on positive results or on bounds. For the Higgs exchange, the $B_d^0 - \bar{B}_d^0$ rate does not depend on the mass scale M which cancels between the mixing coupling to the Higgs and the assumption on the mixing matrix elements, so it does not appear in Eq. (3.3). Instead the rate depends on the Higgs mass from the Higgs propagator. If we fit the $B_d^0 - \bar{B}_d^0$ rate to the tree level Higgs exchange we find

$$M_H \simeq (2.4 \pm 0.6)(f_B/(0.15\mathrm{GeV}))M_Z \simeq (200 - 300)\mathrm{GeV}. \tag{4.1}$$

For the case of the Z^0 FCNC coupling being dominant, the Z^0 mass in the propagator is of course known, but the mixing matrix elements, Eq. (3.4) now are assumed to depend on the new heavy fermion mass scale M. Again, if one fits $B_d^0 - \bar{B}_d^0$ mixing due to Z^0 exchange at tree level one finds that the required heavy fermion mass is

$$M \simeq (275 \pm 66)\ \mathrm{GeV} \times (f_B/0.15\ \mathrm{GeV}). \tag{4.2}$$

It is interesting to note that the observed strength of $B_d^0 - \bar{B}_d^0$ mixing implies that the values of M_H or of M are $O(v = 250\ \mathrm{GeV})$, the scale of the electroweak symmetry breaking; this may not be a numerical coincidence.

We have extended the coupling constants, not only to systems made out of charge $-1/3$ quarks, but also to those of charge $2/3$ quarks, and to leptons. This would be valid if the mass scale responsible for the breaking of the GIM mechanism would be the same for all three of the above systems. Even though this may be unlikely, we do not expect these masses to be orders apart; thus there maybe a rescaling by a small factor as we go from group to group. With these remarks in mind we saw in Ref. [3] that we had no gross violations of any present experimental bounds. We also note that predictions for several, as yet unobserved, processes are close to their present bounds.

In case the observed $B_d^0 - \bar{B}_d^0$ mixing is due to flavor changing couplings of the Higgs scalar H^0, the theory predicts two flavor changing processes (Table I) which are slightly below the present experimental upper limits. These are the ones for $D^0 - \bar{D}^0$ mixing and $BR(\mu^- \to e^-\gamma)$. Sensitivity to $D^0 - \bar{D}^0$ mixing at this level is expected at the tau-charm factory, and this prediction is larger than that of the standard model. It is probably one order of magnitude too small to be used to observe CP violation in this system.

TABLE I. Reactions and Bounds for Higgs Exchange

Reaction	Bound	Present Limit
$r_D(D^0 - \bar{D}^0$ Mixing)	$\leq 2 \times 10^{-3}$	$\leq 5.6 \times 10^{-3}$
$\mathrm{BR}(\tau \rightarrow \mu^-\mu^+\mu^-)$	$\leq 10^{-13}$	$\leq 2.9 \times 10^{-5}$
$\mathrm{BR}(\mu^- \rightarrow e^-\gamma)$	$\leq 10^{-12}$	$\leq 4.9 \times 10^{-11}$

In case the observed $B_d^0 - \bar{B}_d^0$ mixing is due to the flavor changing coupling of Z^0, Table II predicts several flavor changing couplings of Z^0 which may, in the near future, have observable consequences: namely, $BR(\mu^- \rightarrow e^-e^+e^-)$, $D^0 - \bar{D}^0$ mixing, $BR(\tau^- \rightarrow \mu^-\mu^+\mu^-)$, $BR(\mu^- \rightarrow e^-\gamma)$ and the flavor changing decay modes of Z^0 which can be tested with the $10^7 Z^0$'s expected at LEP.

TABLE II. Reactions and Bounds for Z^0 Exchange

Reaction	Bound	Present Limit
$r_D(D^0$-$\bar{D}^0$ Mixing)	$\leq 10^{-3}$	$\leq 5.6 \times 10^{-3}$
$\mathrm{BR}(\tau^- \rightarrow \mu^-\mu^+\mu^-)$	$\leq 10^{-7}$	$\leq 2.9 \times 10^{-5}$
$\mathrm{BR}(\mu^- \rightarrow e^-\gamma)$	$\leq 3 \times 10^{-14}$	$\leq 4.9 \times 10^{-11}$
$\mathrm{BR}(K_L \rightarrow \mu^+\mu^-)$	100 × Limit	9.1×10^{-9}
$\mathrm{BR}(\mu^- \rightarrow e^-e^+\epsilon^-)$	10 × Limit	$\leq 1.0 \times 10^{-12}$
$\mathrm{BR}(Z^0 \rightarrow t\bar{c} + c\bar{t})$	1500×10^{-7}	(for $m_t = 60\,\mathrm{GeV}$)
$\mathrm{BR}(Z^0 \rightarrow b'\bar{b} + b\bar{b}')$	5000×10^{-7}	(for $m_{b'} = 50\,\mathrm{GeV}$)
$\mathrm{BR}(Z^0 \rightarrow \tau'\bar{\tau} + \bar{\tau}'\tau)$	1000×10^{-7}	(for $m_\tau = 40\,\mathrm{GeV}$)

The process $\tau^- \rightarrow \mu^-\mu^+\mu^-$ is just at the limit where it could be observed at the τ-charm factory, and the $D^0 - \bar{D}^0$ mixing is at the same observable level as with Higgs exchange. The apparent violations of the limits for $K_L \rightarrow \mu^+\mu^-$ and $\mu^- \rightarrow e^-e^+e^-$ result from the large extrapolation of the mixing matrix elements mass dependence to transitions between the lightest quarks and leptons, and may not signal serious discrepancies of the scheme for more massive quarks and leptons. If they are real discrepancies, however, the predictions may have to be scaled down by one or two orders of magnitude. The large branching ratios for Z^0 to heavy top quarks or fourth generation quarks or leptons show the possibility that the τ-charm factory may complement LEP in verifying or ruling out such flavor changing processes. If the top quark is more massive than the Z^0 and there is no fourth generation, then the tau-charm factory will be very important for testing exotic new heavy fermions.

V. SUMMARY AND CONCLUSION

In this talk, we investigated the implications of the possibility that the observed

$B_d^0 - \bar{B}_d^0$ mixing is due to small flavor changing couplings of the Higgs scalar, H^0, or the Z^0, induced by new physics at an energy scale beyond the standard model. The implications are rich and the predictions for future experiments at a τ-charm factory and at LEP are summarized in the Tables. Moreover, the scale associated with the new physics, M, and/or the mass of the Higgs scalar seem to coincide with the Higgs vacuum expectation value, $v = 250$ GeV. This may not be a coincidence but may indicate that this new region will indeed show up at a mass scale of 250 GeV.

Although our discussions were made in the context of a model of ordinary fermions mixing with heavy, exotic ones, the general structure of these flavor changing couplings should be valid in a broader class of theories. CP violation could be included in such a class of models; as the GIM mechanism is violated, an electric dipole moment[4] could be induced at the one loop level. Likewise these effects would become stronger with increasing quark mass.

VI. ACKNOWLEDGEMENTS

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