FLAVOR CHANGING NEUTRAL CURRENTS IN CHARM SECTOR†
(as signal for new physics)

S. PAKVASA
Department of Physics & Astronomy
University of Hawaii at Manoa
Honolulu, HI 96822

1 Introduction
I would like to discuss $D^0 - \bar{D}^0$ the mixing and rare D decays as manifestations of Flavor Changing Neutral Currents (FCNC) in the charm sector. I will first review the expectations in the Standard Model (SM) and then summarize some typical expectations in new physics scenarios1. I would like to argue that the charm case offers a large window of opportunity and it may be possible to learn something about the origin of the fermion mass matrix.

2 $D^0 - \bar{D}^0$ Mixing
$D^0 - \bar{D}^0$ mixing differs from $K^0 - \bar{K}^0$ and $B^0 - \bar{B}^0$ mixing in several ways. In the box diagram, the s-quark intermediate state dominates; this is in spite of the suppression by the factor $(m_s/m_c)^2$ resulting from the external momenta (i.e. the fact that $m_c > m_s$). The final result for $\delta m$ from the box diagram is extremely small, one finds

$$\delta m_D \sim 0.5 \times 10^{-17} \text{ GeV}$$

(1)

for $m_s \sim 0.2$ GeV and $f_D \sqrt{B_D} \sim 0.2$ GeV; leading to

$$\frac{\delta m_D}{\Gamma_{D^0}} \sim 3 \times 10^{-5}$$

(2)

Although (or rather because) the short distance box diagram gives such a small value, it has been a long-standing concern that the long distance effects may

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enhance $\delta M$ considerably. We have begun a systematic dispersive approach; evaluating contributions from single particle intermediate states, two particle intermediate states and so on. We have found that $(\delta M)_{1p} \sim 0.4 \times 10^{-16}$ GeV and $(\delta M)_{2p}$ (due to $p^+p^-$ states) $\sim 10^{-16}$ GeV. It can be shown that the contributions from PV, VV and multiparticle states are kinematically suppressed further. In absence of conspiracies, we conclude $\delta M \sim 10^{-16}$ GeV. Georgi and collaborators apply HQET to the matrix element: assume that $m_c$ is much larger than typical hadronic scale, match the effective low energy theory at $m_c$ and then run to low energies. No new operators arise and all long distance effects should come from the running. The only operators then are the 4 quark operator yielding the usual box result; a 6-quark operator which is about 3 times the box and an 8-quark operator which is about half the box. The net result is a moderate ($\sim 3-4$) enhancement with $\delta M \sim 10^{-16}$ GeV in agreement with the dispersive estimate above. Hence the SM expectation for $\delta M$ including long distance effects, is

$$\delta M \sim 10^{-16} \text{ GeV}$$  \hspace{1cm} (3)

and hence $x = \delta M/\Gamma \sim 10^{-4}$. We expect $\delta \Gamma$ to be of the same order as $\delta M$ and hence $y = \delta \Gamma/2\Gamma \sim 10^{-4}$. The SM expectation for the mixing parameter $r_{mix}$ given by

$$r_{mix} = \frac{x^2 + y^2}{2 + x^2 + y^2}$$  \hspace{1cm} (4)

is $(r_{mix})_{SM} \sim 10^{-8}$. Hence there are more than 5 orders of magnitude to search for new physics (the current bound on $r_{mix}$ is $5 \times 10^{-3}$).

CP violation in mixing can be described by two parameters related to the conventional $p$ and $q$:

$$\frac{2Re \; \epsilon_D}{1+|\epsilon_D|^2} = \frac{1-|q/p|^2}{1+|q/p|^2} \text{ and}$$

$$tan\phi = \frac{Im(q/p)}{Re(qp)}$$  \hspace{1cm} (5)

For the $D^0 - \bar{D}^0$ system, the SM values are

$$2Re \; \epsilon_D \approx \frac{1}{2} \frac{\delta \Gamma}{\delta M} \left[ \frac{Im \Gamma_{12}}{Re \; \Gamma_{12}} - \frac{Im \; M_{12}}{Re \; M_{12}} \right] \sim 5 \times 10^{-3}$$  \hspace{1cm} (6)

and $tan\phi \approx -Im \; M_{12}/Re \; M_{12} \sim 10^{-2}$. The phase angle $\phi$ is convention dependent and not measurable; but accessible in combination with amplitude phases.
There are several ways to measure Re$\epsilon_D$: (i) comparing the time integrated rates for $D^0$ and $\bar{D}^0$ to a CP eigenstate final state, the asymmetry $A = (\Gamma - \Gamma)/(\Gamma + \Gamma) \cong Re \epsilon_D$ (ii) the charge asymmetry in $e^+e^- \to D^0\bar{D}^0 \to \ell^+\ell^-x, \ell^-\ell^-x$, $a = (N^{++} - N^{--})/(N^{++} + N^{--}) \cong 2Re \epsilon_D$.

The time dependent decay rates into flavor specific states for states starting as $D_0$ (and $\bar{D}_0$) are interesting and useful. The modes into $K^+\pi^-$ and $K^-\pi^+$ have been much discussed recently. One interesting result is that if new physics enhances both $\delta M$ and $\phi$, then the difference in the rates $\Gamma(D^0 \to K^+\pi^-(t)) - \Gamma(\bar{D}^0 \to K^-\pi^+(t))$ is proportional to $(\sin \phi)\delta M$ at short times and this linear time dependence should be “easy” to disentangle.

3 Rare Decays

The flavor changing radiative decay which is analogous of the famous $b \to s\gamma$ is $c \to u\gamma$. The bare electro-weak penguin for $c \to u\gamma$ yields a branching ratio of $10^{-17}$ which is enhanced to $10^{-12}$ by QCD corrections. This would seem to leave a large window for new physics contributions. Unfortunately, long distance effects are very large and close this window. Conventional nearby poles make rates for decays like $D \to \rho\gamma$ in the range $10^{-4} - 10^{-6}$. Hence both the Penguin as well as any new physics are completely masked by these long distance effects. Similar long distance effects plague decays with off-shell photons such as $D \to \ell^+\ell^-x$. However, observation and study of these decay modes would be very useful in understanding long distance physics.

There are a number of other rare (one-loop) decay modes of $D$ which do have extremely small rates when evaluated in SM; thus providing a potential window for new physics contributions.

(i) $D^0 \to \mu^+\mu^-$

At one loop level the decay rate for $D^0 \to \mu^+\mu^-$ is given by

$$\Gamma(D^0 \to \mu^+\mu^-) = \frac{G_F^4 m_W^4 f_D^2 m_\mu m_{D^0}}{32\pi^3} |F|^2 \sqrt{1 - 4m_\mu^2/m_{D^0}^2}$$

(7)

where

$$F = \begin{align*}
U_{us} U_{cs}^* (x_s + 3/4 x_s^2 \ell_n x_s) \\
U_{ub} U_{cb}^* (x_b + 3/4 x_b^2 \ell_n x_b)
\end{align*}$$

and $x_i = m_i^2/m_W^2$. This yields a branching fraction of $10^{-19}$. There are potentially large long distance effects; e.g. due to intermediate states such as $\pi^0, K^0, K^0, \eta, \eta'$ or $(\pi\pi, K\bar{K})$ etc. Inserting the known rates for $P_{i} \to \mu^+\mu^-$ and ignoring the extrapolation the result for $B(D^0 \to \mu^+\mu^-)$ is $3.10^{-15}$. 

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This is probably an over-estimate but gives some idea of the long distance enhancement.

(ii) $D^0 \rightarrow \gamma \gamma$

The one loop contribution to $D^0 \rightarrow \gamma \gamma$ can be calculated in exactly the same way as above and the amplitude $A$ is found to be approximately $4.6 \times 10^{-14}$ GeV, where $A$ is defined by the matrix element $A q_1\mu q_2\nu \epsilon_{1\rho} \epsilon_{2\sigma} \epsilon^{\mu\nu\rho\sigma}$.

The decay rate is $\Gamma = \frac{|A|^2}{192\pi^3}$ and the branching fraction is $10^{-16}$. The single particle contributions due to $(\pi, K, \eta, \eta')$ yield $3 \times 10^{-9}$ but again are probably over estimated.

(iii) $D \rightarrow \nu \bar{\nu} x$.

The decay rate for $c \rightarrow u\nu \bar{\nu}$ (for 3 neutrino flavors) is given by

$$\Gamma = \frac{3G^2_F m^2_c}{192\pi^3} \left[ \frac{\alpha}{4\pi f_w} \right]^2 |A_\nu|^2.$$  (9)

Inserting the one loop value for $A_\nu$, one finds for the branching fractions:

$$B(D^0 \rightarrow \nu \bar{\nu} x) = 2.1 \times 10^{-15}$$
$$B(D^+ \rightarrow \nu \bar{\nu} x) = 4.5 \times 10^{-15}$$  (10)

For the exclusive modes $D^0 \rightarrow \pi \nu \bar{\nu}$ and $D^+ \rightarrow \pi^+ \nu \bar{\nu}$ an estimate of the long distance contributions yields

$$B(D^0 \rightarrow \pi^0 \nu \bar{\nu}) \approx 5.6 \times 10^{-16}$$
$$B(D^+ \rightarrow \pi^+ \nu \bar{\nu}) \approx 8.1 \times 10^{-16}$$  (11)

(iv) $D \rightarrow \bar{K}(K)\nu \bar{\nu}$

These modes have no short distance one loop contributions. Estimates of long distance contributions due to single particle poles yield branching fractions of the order of $10^{-15}$.

4 Direct CP Violation

Simplest examples of direct CP violation are rate asymmetries for $D^+$ and $D^-$ decays into charge conjugate final states. As in now well-documented\cite{1}, to obtain non-zero asymmetries one needs i) at least two strong interaction eigenstates in the final state (e.g. isospins) with unequal final state interaction phases and ii) with unequal weak CP phases. The important and crucial feature of SM is that these conditions are satisfied only in the Cabibbo-suppressed modes. Hence no CPV rate asymmetry is expected for Cabibbo-favored modes (e.g. $D^+ \rightarrow K^- \pi^+ \pi^+$) or for doubly-Cabibbo- suppressed modes (e.g. $D^+ \rightarrow K^+ \pi^0$). For the Cabibbo-suppressed modes the asymmetry can be no larger
than of order $10^{-3}$; $D \to \rho \pi$ seems to be a promising candidate according to some recent estimates.

5 New Physics Scenarios

(i) Additional Scalar Doublet

One of the simplest extensions of the standard model is to add one scalar Higgs doublet. If one insists on flavor conservation there are two possible models: in one (model I) all quarks get masses from one Higgs (say $\phi_2$) and the other $\phi_1$ does not couple to fermions; in the other $\phi_2$ gives masses to up-quarks only and $\phi_1$, to down-quarks only. The new unknown parameters are $\tan \beta (= v_1/v_2$, the ratio of the two vevs) and the masses of the additional Higgs scalars, both charged as well as neutral.

In the charmed particle system, the important effects are in $\delta m_D$ and the new contributions due to charged Higgses to rare decays such as $D^0 \to \mu^+\mu^-$, $D \to \pi\ell\bar{\ell}$, $D \to \gamma\gamma$, $D \to \rho\gamma$ etc.

The mass of the charged Higgs is constrained to be above 50 GeV by LEP data and there is a joint constraint on $m_H$ and $\tan \beta$ from the observation of $b \to s\gamma$. For large $\tan \beta$, $\delta m_D$ can be larger than the SM results.

(ii) Fourth Generation

If there is a fourth generation of quarks, accompanied by a heavy neutrino ($M_{N^0} > 50$ GeV to satisfy LEP constraints) there are many interesting effects observable in the charm system.

In general $U_{ub'}$ and $U_{cb'}$ will not be zero and then the $b'$-quark can contribute to $\delta m_D$ as well as to rare decays such as $D^0 \to \mu\bar{\mu}$, $D \to \ell\bar{\ell}x$, $D \to \nu\bar{\nu}$ etc. (A singlet $b'$ quark as predicted in E6 GUT has exactly the same effect). A heavy fourth generation neutrino $N^0$ with $U_{eN^0}U_{\mu N^0} \neq 0$ engenders decays such as $D^0 \to \mu\bar{\mu}$ as well.

For $U_{ub'}U_{cb'} \gtrsim 0.01$ and $m_{b'} > 100$ GeV, it is found that

(a) $\delta m_D/\Gamma > 0.01$;

(b) $B(D^0 \to \mu\bar{\mu}) > 0.5 \times 10^{-11}$;

(c) $B(D^+ \to \pi^+\ell\bar{\ell}) > 10^{-10}$; etc.

For a heavy neutrino of mass $M_{N^0} > 45$ GeV, the mixing with $e$ and $\mu$ is bounded by $|U_{eN}U_{N\mu}|^2 < 7.10^{-6}$ and we find [4] that branching fraction for $D^0 \to \mu^-e^+, \mu^+e^-$ can be no more than $6.10^{-22}$. This is also true for a singlet heavy neutrino unaccompanied by a charged lepton. To turn this result around, any observation of $D^0 \to \mu e$ at a level greater than this must be due to some other physics, e.g. a horizontal gauge (or Higgs) boson exchange.
(iii) Singlet $Q = 2/3$ Quarks

In this case, there is a new contribution to $\delta M$ at the tree level due to FCNC coupling to $Z$ giving\(^7\)

$$\delta M_D = \frac{\sqrt{2}}{3} G_F f_D^2 B_D m_D \eta_{QCD} \lambda$$  \hspace{1cm} (12)

where $\lambda = \sum_{i=1}^{3} V_{ui} V_{ci}^*$ indicates the lack of unitarity of the 3x3 KM matrix. $\delta M_D$ can be as large as $10^{-15}$ GeV. The angle $\phi$ is given by

$$\tan \phi \approx \frac{\text{Im}(V_{ub} V_{cb})^2}{\text{Re}(V_{ub} V_{cb}^*)^2}$$  \hspace{1cm} (13)

and can be large. This form for $\tan \phi$ is valid in several scenarios, including those with charged Higgses.

(iv) Flavor Changing Neutral Higgs

It has been an old idea that if one enlarges the Higgs sector to share some of the large global flavor symmetries of the gauge sector (which eventually are broken spontaneously) then it is possible that interesting fermion mass and mixing pattern can emerge. It was realized early\(^8\) that in general this will lead to flavor changing neutral current couplings to Higgs. As was stressed\(^9\) then and has been emphasized recently\(^10\), this need not be alarming as long as current limits are satisfied. But this means that the Glashow-Weinberg criterion will not be satisfied and the GIM mechanism will be imperfect for coupling to scalars. This is the price to be paid for a possible ”explanation” of fermion mass/mixing pattern. Of course, the current empirical constraints from $\delta m_K, K_L \rightarrow \mu \mu, K_L \rightarrow \mu e$ etc. must be observed. This is not at all difficult. For example, in one early model, flavor was exactly conserved in the strange sector but not in the charm sector!

In such theories, there will be a neutral scalar, $\phi^0$ of mass $m$ with coupling such as

$$(g \bar{\mu} \gamma_5 c + g' \bar{c} \gamma_5 u) \phi^0$$  \hspace{1cm} (14)

giving rise to a contribution to $\delta m_D$

$$\delta m_D \sim \frac{gg'}{m^2} f_D^2 B_D m_D (m_D/m_C)$$  \hspace{1cm} (15)

With a reasonable range of parameters, it is easily conceivable for $\delta m_D$ to be as large as $10^{-13}$ GeV. There will also new contributions to decays such as $D^0 \rightarrow \mu \bar{\mu}, D^0 \rightarrow \mu e$ which will depend on other parameters.
There are other theoretical structures which are effectively identical to this, e.g., composite technicolor. The scheme discussed by Carone and Hamilton\cite{21} leads to a $\delta m_D$ of $4.10^{-15}$ GeV.

(v) Family Symmetry

The Family symmetry mentioned above can be gauged as well as global. In fact, the global symmetry can be a remnant of an underlying gauged symmetry. A gauged family symmetry leads to a number of interesting effects in the charm sector\cite{22}.

Consider a toy model with only two families and a $SU(2)_H$ family gauge symmetry acting on LH doublets; with

$$\left[ \begin{array}{c} u \\ c \\ \end{array} \right] \left[ \begin{array}{c} d \\ s \\ \end{array} \right]_L \quad \text{and} \quad \left[ \begin{array}{c} \nu_e \\ \nu_\mu \\ \end{array} \right] \left[ \begin{array}{c} e \\ \mu \\ \end{array} \right]_L$$

assigned to $I_H = 1/2$ doublets. The gauge interaction will be of the form:

$$g \left[ (d \ s)_L \gamma_\mu \bar{\tau} G_\mu \left( \begin{array}{c} d \\ s \\ \end{array} \right)_L + \ldots \right] \quad (16)$$

After converting to the mass eigenstate basis for quarks, leptons as well as the new gauge bosons, we can calculate contributions to $\delta m_K, \delta m_D$ as well as to decays such as $K_L \to e\mu$ and $D \to e\mu$. The results depend on $\theta_d, \theta_u$ and $\theta_e$ which are the unknown mixing angles in the $d_L - s_L$, $u_L - c_L$ and $e_L - \mu_L$ sectors and the gauge boson masses. It is possible to obtain $\delta m_D \sim 10^{-13}$ GeV and $B(D^0 \to e\mu) \sim 10^{-13}$ while satisfying the bounds on $\delta m_K$ and $B(K^0_L \to e\mu)$.

(vi) Supersymmetry

In the Minimal Supersymmetric Standard Model new contributions to $\delta m_D$ come from gluino exchange box diagram and depend on squark mixings and mass splittings. To keep $\delta m_K^{SUSY}$ small the traditional ansatz has been squark degeneracy. In this case $\delta m_D^{SUSY}$ is also automatically suppressed, no more than $10^{-18}$ GeV. It has been proposed that another possible way to keep $\delta m_K^{SUSY}$ small is to assume not squark degeneracy but proportionality of the squark mass matrix to the quark mass matrix. It turns out in this case that $\delta m_D$ can be as large as the current experimental limit. In a very recent proposal of “effective supersymmetry” which is a new approach to the problem of FCNC in supersymmetry, there could be also significant contributions to $\delta m_D$.\[7]
(vii) Left-Right Symmetric Models

In general Left-Right symmetric theories do not lead to interesting predictions for the D system. There is one exception: as pointed out by the Orsay group, it is possible to obtain sizable direct CPV rate asymmetries in Cabibbo-allowed modes.

Conclusion

My personal prejudice is that if we are to understand fermion mass/mixing pattern at accessible energy scales, then GIM violation and FCNC must exist; and the charm system offers the largest window of opportunity for this search. They must be found!

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