Charm as Probe of New Physics

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1 Introduction

In this talk I would like to discuss two aspects of charm physics. One is to show that many standard model predictions for rare decay modes (along with $D^0 - \bar{D}^0$ mixing and CP violation) are extremely small thus opening a window for new physics effects[1]; and the other is to review the expectations from several plausible and interesting new physics possibilities.

The standard model will be taken to be defined by the gauge group $SU(3)_c \times SU(2)_L \times U(1)$ with three families of quarks and leptons, one Higgs doublet and no right handed neutrinos (thus $m_{\nu_i} = 0$). We will review predictions for D mixing, CP violation in the D system and then discuss rare decays of D's.

Everything in this talk is based upon joint on-going work with Gastavo Burdman, Eugene Golowich and JoAnne Hewett; many details and complete results will appear in a forthcoming review.

2 $D - \bar{D}$ Mixing and CP Violation

As already discussed by Burdman,[2] $D^0\bar{D}^0$ 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 $m_c > m_s$)[3]. The final result for δm from the box diagram is extremely small, one finds

$$\delta m_D \sim \quad 0.5.10^{-17} \ \ GeV \tag{1}$$

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

$$\delta m_D/\Gamma_{D^0} \ \sim \ 3.10^{-5} \tag{2}$$

One should worry whether long distance contributions would give much larger contributions. The contribution from two body states K^+K^-, $K^-\pi^+, K^+\pi^-, \pi^+\pi^-$ was carefully evaluated by Donoghue et al. [4] With the current experimental values, this is rather small, of the same order as above. A very different calculation of the matrix element resulting from the box diagram due to Georgi et al. [5] employing HQET also yields an enhancement of no more than a factor of 4-5 over the short distance result. Even if none of these arguments are completely convincing it is likely that the SM $\delta m/\Gamma$ is not enhanced by more than an order of magnitude over the short distance value of 3.10^{-5}. Since the current experimental limit [6] is 0.083, there is plenty of room for new physics effects to show up.

CP violation in mixing is described by ϵ_D and the asymmetry a in e.g. $e^+e^- \to D^0\bar{D}^0 \to \ell^+\ell^+x, \ell^-\ell^-x$ defined by $a = (N^{++}-N^{--})/(N^{++}+N^{--})$ goes as $2Re\ \epsilon_D$ for small ϵ_D. $2Re\ \epsilon_D$ is given by

$$2Re\ \epsilon_D \ = \ \frac{2Im\ (M_{12}\Gamma_{12}^*)}{\mid (Im\ M_2) \mid^2 + \mid (Re\Gamma_{12} \mid^2} \tag{3}$$

It is always possible to choose a phase convention for the KM matrix such that $Im\Gamma_{12} = 0$. Then

$$2Re\ \epsilon_D \leq \left(\frac{Im\ M_{12}}{(Re\Gamma_{12})}\right) \tag{4}$$

the left hand side is given by $\left(\frac{m_b m_c}{m_s^2}\right)^2\ Im(U_{cb}\ U_{bu^*})^2/\theta_c^2$ and hence

$$2Re\ \epsilon_D \leq\ 10^{-2}. \tag{5}$$

This is the maximum value for the CP violating charge asymmetry (due to mixing) in the SM. The actual value lies between 5.10^{-3} and 5.10^{-4}.

Direct CP violation can also be looked for in partial rate asymmetries of charge conjugate states. Such rate asymmetries are proportional to $\sin(\phi_i - \phi_j)\sin(\delta_i - \delta_j)$ where ϕ_i are weak CP phases, δ_i are final state interaction phases and i, j are strong interaction eigenstates [7]. In SM for D (and Ds) decays there can be no CP violating rate asymmetries for the Cabibbo allowed decay modes (and for the double Cabibbo-suppressed modes as well) to the lowest order. In Cabibbo-suppressed modes there can be interference between the quark decay diagram and Penguin (and/or annihilation) diagram leading to CP violating partial rate asymmetries. The main difficulty is evaluating the final state interaction phases. Several groups have estimated these phases[8] and based on these the more promising candidates seem to be $D_s^+ \to K^{*+}\eta(\eta')$ and $D^+ \to \bar{K}^{*0}K^+(\rho^0\pi^+)$ with asymmetries in the range of $(2\text{-}8)10^{-3}$.

3 Rare Decays

There are a number of "rare" (one-loop) decay modes of D[9] which 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

$$\Gamma(D^0 \to \mu^+\mu^-) \ = \frac{G_F^4 \ m_W^4 \ f_D^2 \ m_\mu^2 \ m_D \mid F \mid^2}{32\pi^3} \sqrt{1 - 4m_\mu^2/m_D^2} \tag{6}$$

where

$$\begin{aligned} F = \ & U_{us}U_{cs}^* \ (x_s + 3/4 \ x_s^2 \ \ell_n x_s) \\ & U_{ub}U_{cb}^* \ (x_b + 3/4 \ x_b^2 \ell_n x_b) \end{aligned} \tag{7}$$

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 $\pi^0, K^0, \bar{K}^0, \eta, \eta')$ 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}. This is probably an over-estimate but might give some idea of the long distance effects.

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

The one loop contribution to $D^0 \to \gamma\gamma$ can be calculated in exactly the same way as above and the amplitude A is found to be approximately $4.6.10^{-14}$ 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 $\Gamma = \mid A \mid^2 m_D^3/64\pi$ and the branching fraction is 10^{-16}. The single particle contributions due to (π, K, η, η') yield 3.10^{-9} but again are grossly over estimated.

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

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

$$\Gamma = \frac{3G_F^2 \ m_c^5}{192\pi^3} \left[\frac{\alpha}{4\pi x_w}\right]^2 \mid A_\nu \mid^2 . \tag{8}$$

Inserting the one loop value for A_ν, one finds for the branching fractions:

$$\begin{aligned} B(D^0 \to \nu\bar{\nu}x) &= 2.10^{-15} \\ B(D^+ \to \nu\bar{\nu}x) &= 4.5.10^{-15} \end{aligned} \tag{9}$$

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

$$\begin{aligned} B(D^0 \to \pi^0\nu\bar{\nu}) &\sim 5.6.10^{-16} \\ B(D^+ \to \pi^+\nu\bar{\nu}) &\sim 8.10^{-16} \end{aligned} \tag{10}$$

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

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

(v) $D \to \ell\bar{\ell}x$.

The one loop contributions from γ, Z and WW intermediate states give for the inclusive decay mode $c \to u\ell\bar{\ell}$ a rate which corresponds to a branching fraction for D^+ of the order

$$B.R.(D^+ \to \ \ell\bar{\ell}x) \ = 2.10^{-10} \tag{11}$$

This corresponds to a fraction for D^0 of B.R. $(D^0 \to \ell\bar{\ell}x) \ = 10^{-10}$. The exclusive modes $D^+ \to \pi^+\ell\bar{\ell}$ and $D^0 \to \pi^0\ell\bar{\ell}$ are expected to have somewhat smaller branching fractions in the range of a few times 10^{-11}.

(vi) $(D \to \gamma x.)$

The Penguin diagram can give rise to $c \to u\gamma$ at one loop level and (before short distance QCD corrections) gives a rate for $c \to u\gamma$ corresponding to a branching fraction of B.R. $(D \to \gamma x)$ of about 10^{-16}. This would yield branching fractions for exclusive channels such as $D^0 \to \rho^0\gamma, w^0\gamma$ at a level of 10^{-17} or so. It is expected that the QCD corrections will enhance this rates (these calculations are in progress).

On the other hand, if the precise partial wave structure in the amplitude for the decays such as $D \to \phi\rho$ (as well as the total rates) were known, it is possible to estimate the rates for $D^0 \to \phi^0\gamma, D \to \rho\gamma$ etc. At present only upper bounds can be obtained e.g.

$$\begin{array}{lcl} B.R.(D^+ \to \rho^+\gamma) & < & 2.10^{-4} \\ B.R.(D^0 \to \rho^0\gamma) & < & 2.10^{-5} \\ B.R.(D^0 \to \phi\gamma) & < & 2.10^{-4} \end{array} \tag{12}$$

If these long distance contributions turn out to be much larger than the Penguin contributions (even after QCD correction) then the Penguin will remain invisible in D decays. I suspect that this is the case.

From the data on $D^0 \to \bar{K}^{*0}\rho^0$[6] and VMD one obtains B.R. $(D^0 \to \bar{K}^{*0}\gamma) \sim 1.6.10^{-4}$. From the data on $D^+ \to \bar{K}^{*0}\rho^+$, assuming that $\mid A_1 \mid \gg \mid A_3 \mid$ and that there is no particular enhancement in DCSD mode $D^+ \to K^{*+}\rho^0$, one finds B.R. $(D^+ \to \bar{K}^{*+}\rho^0) \sim 1.4.10^{-4}$ and in turn B.R. $(D^+ \to \bar{K}^{*+}\gamma) \sim 3.10^{-7}$.

I should stress that in all of the above the short distance QCD corrections have not yet been incorporated. Since these tend to enhance the decay rates and the long distance values tend to be over-estimates, the gap between the two will be smaller than it appears here.

4 New Physics Scenarios

(i) Additional Scalar Doublet

One of the simplest extensions of the standard model is to add one scalar Higgs doublet[10]. If one insists on flavor conservation there are two possible models: in one (model I) all quarks get masses from one Higgs (say ϕ_2) and the other ϕ_1 does not couple to fermions; in the other ϕ_2 gives masses to up-quarks only and ϕ_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 δm_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 $B \to K^*\gamma$. For large $\tan\beta$, δm_D can be larger than the SM results[11].

(ii) Fourth Generation

If there is a fourth generation of quarks, accompanied by a heavy neutrino ($M_{N0} > 50$ 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 δm_D as well as to rare decays such as $D^0 \to \mu\bar{\mu}, D \to \ell\bar{\ell}x, D \to \pi\nu\bar{\nu}$ etc. (A singlet b' quark as predicted in E6 GUT has exactly the same effect). A heavy fourth generation neutrino N^0 with $U_{eN0}U^*_{\mu N} \neq 0$ engenders decays such as $D^0 \to \mu\bar{e}$ as well.

For $U_{ub'}U_{cb'} \stackrel{\sim}{>} 0.01$ and $m_{b'} > 100 GeV$, it is found that[12]

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

(b) $B(D^0 \to \mu\bar{\mu}) > 0.5.10^{-11}$;

(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 μ is bounded by $| U_{Ne}U^*_{N\mu} |^2 < 7.10^{-6}$[13] and we find 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) 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 that in general this will lead to flavor changing neutral current couplings to Higgs[14]. As was stressed[15] then and has been emphasized recently[16], 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 $\delta m_K, K_L \to \mu\mu \; K_L \to \mu e$ 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[14]!

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

$$(g\bar{u}\gamma_5 c \ + \ g'\bar{c}\gamma_5 u)\phi^0 \tag{13}$$

giving rise to a contribution to δm_D

$$\delta m_D \sim \ \frac{gg'}{m^2}\, f_D^2 \ B_D \ m_D \, (m_D/m_C) \tag{14}$$

With a reasonable range of parameters, it is easily conceivable for δm_D to be as large as 10^{-13} GeV. There will also new contributions to decays such as $D^0 \to \mu\bar{\mu}, D^0 \to \mu e$ 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 leads to a δm_D of 4.10^{-15} GeV[17].

(iv) 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[18].

Consider a toy model with only two families and a $SU(2)_H$ family gauge symmetry acting on LH doublets; with $\left[\binom{u}{c}_L \ \binom{d}{s}_L\right]$ and $\left[\binom{\nu_e}{\nu_\mu}_L \ \binom{e}{\mu}_L\right]$ assigned to $I_H = 1/2$ doublets. The gauge interaction will be of the form:

$$g\left[(\bar{d} \ \bar{s})_L \ \gamma_\mu \ \bar{\tau}.\bar{G}\mu \begin{pmatrix} d \\ s \end{pmatrix}_L \quad + ...\right] \tag{15}$$

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 are:

$$\begin{array}{lcl} \delta m_D/\delta m_K & = & \frac{f_D^2 B_D m_D \left[\frac{\cos^2 2\theta u}{m_1^2} \ + \frac{\sin^2 2\theta u}{m_2^2} - \frac{1}{m_3^2}\right]}{f_K^2 B_K m_K [d \to u]} \\ m(K_L^0 \to e\mu) & = & \frac{1}{2\sqrt{2}} g^2 f_K m_\mu \left[\frac{\cos 2\theta_d cos 2\theta_e}{m_1^2} \ + \ \frac{\sin 2\theta_d \sin 2\theta_e}{m_2^2}\right] \bar{\mu}(1+\gamma_5)e. \\ m(D^0 \to e\mu) & = & \frac{1}{4} g^2 f_K m_\mu \, [d \to u] \, \bar{\mu}(1+\gamma_s)e. \end{array} \tag{16}$$

where θ_d, θ_u are θ_e are the mixing angles in the $d_L - s_L$, $u_L - c_L$ and $e_L - \mu_L$ sectors and are not measured experimentally and m_i are the gauge 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 δm_K and $B(K_L^0 \to e\mu)$.

(v) Supersymmetry

In the Minimal Supersymmetric Standard Model new contributions to δm_D come from gluino exchange box diagram and depend on squark mixings and mass splittings. To keep δm_K^{SUSY} small the traditional ansatz has been squark degeneracy. In this case δm_D^{SUSY} is also automatically suppressed, no more than 10^{-18} GeV [19]. Recently it has been proposed[20] that another possible way to keep δm_K^{SUSY} small is to assume not squark degeneracy but proportionality of the squark mass matrix to the quark mass matrix to the quark mass matrix. It turns out in this case that δm_D can be as large as the current experimental limit. In some non-minimal SUSY theories certain radiative decay modes can have large rates[21].

(vi) Left-Right Symmetric Models

In a very nice paper[22], the Orsay group has pointed out that in left-right symmetric extensions of the SM, there can be sizable CP violating asymmetries in the Cabibbo allowed decay modes (which is impossible in the SM). I would like to illustrate this but in a different kind of model, the model of Gronau and Wakaizuni[23].

Recall that the basic premise of the model is that the suppression of $b \to c\ell\nu$ decays is not due to a small mixing U_{bc} but due to the decay proceeding via W_R exchange and the smallness of the ratio $(m_{W_L}/m_{W_R})^2$. This is accomplished by enlarging the gauge group to $SU(2)_L \times SU(2)_R \times U(1)$ but without manifest left-right symmetry and assuming the two mixing matrices to be

$$U_L = \begin{pmatrix} 1 & \lambda & \rho\lambda^3 \\ -\lambda & 1 & 0 \\ -\rho\lambda^3 & -\rho\lambda^4 & 1 \end{pmatrix} \tag{17}$$

$$U_R = \begin{pmatrix} e^{i\alpha} & 0 & 0 \\ 0 & se^{i\delta} & ce^{i\beta} \\ 0 & ce^{i\gamma} & -se^{i(\beta+\gamma)} \end{pmatrix} \tag{18}$$

where λ and ρ are the usual Wolfenstein parameters and U_L is real. As is evident, the current $b \to c$ is pure RHC. For successful phenomenology and a good fit to all the data there are a number of constraints on the model; e.g. ν_R must have a mass in the range of few MeV, $\rho \sim 0.2$ to 0.7, $m_{WR} > 400$ GeV, $c > 0.8, s < 0.6$. All CP violation comes from the RH sector and ϵ and ϵ' require that: $\sin(\gamma - \alpha) > 0.1, \sin(\delta - \alpha) < 0.5$ and $\sin(\alpha + w) < 0.7$; thus the constraints on the phases in U_R are rather weak.

In this model, for a decay such as $D \to \bar{K}\pi$, in addition to the W_L mediated decay there is an additional amplitude due to W_R which now carries a CP phase. Because of the larger W_R mass, the QCD coefficients for the RR operators are different from the LL operators resulting in a different ratio for the $I = 3/2$ to $1/2$ final states from the two operators; hence $a_{3R}/a_{1R} \neq a_{3L}/a_{1L}$. Then the CP partial rate asymmetry for the decay mode $D^0 \to K^-\pi^+$ and $\bar{D}^0 \to K^+\pi^-$ is given by

$$\frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} = \frac{s(a_{3R} - a_{1R})}{a_{1L}} \ \sin(\delta_1 - \delta_3) \ \sin(\alpha - \delta) \tag{19}$$

where we have taken from data $a_{1L} \sim a_{3L}$. If, for simplicity, we take $a_{1R} \gg a_{3R}$, then the RHS becomes

$$s\,(m_{W_L}/m_{W_R})^2 \quad \sin(\delta_1 - \delta_3)\sin(\alpha - \delta). \tag{20}$$

Taking $s \sim 0.5$, $\sin(\alpha - \delta) \sim 0.5$ in the allowed range, $\delta_1 - \delta_3 \sim 0(90^0)$ from data, and $(m_{W_L}/m_{W_R})^2 \sim 0.04$ the asymmetry is of the order 0.01 to be compared to 0 in SM. As shown in Ref. [22] similar values obtain in other left-right symmetric models as well making this a generic result in Left-Right Symmetric theories. Incidentally, the new contributions to δm_D are no larger than in SM.

5 Conclusion

To summarize, in the charm system several phenomena (such as δm, CP, loop induced decays) which are easily observed in K and B system are greatly suppressed in SM and there is a window of opportunity for new physics to show up.

Of course, even when there is new physics beyond the standard model (BSM) it is not guaranteed that there are interesting signals large enough to be seen. Probably the most likely place for some new physics to show up in δm_D. To disentangle the origin some other effects have to be seen. CP violation (in channels forbidden in SM) and rare decays such as $D^0 \to \mu\bar{\mu}, \gamma\gamma, \nu\nu x$ etc. would come a close second. Decays such as $D^0 \to \mu e$ are probably unlikely to occur at rates large enough to be seen in the near future but who knows?

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