

Charm Mixing and CP-violations - Theory

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This document describes my talk at the 6th Flavor Physics and CP Violation Conference held at Taiwan National University (5/5/08-5/9/08). I begin by commenting on the most recent experimental compilation of D^0 mixing data, emphasizing the so-called ‘strong phase’ issue. This is followed by a review of the theory underlying charm mixing, both Standard Model and New Physics. The mechanism of RP-violation is used to illustrate the methodology for New Physics contributions and the relation of this to rare D^0 decays is pointed out. Finally, I address the subject of CP-violating asymmetries by describing some suggestions for future experimental studies and a recent theoretical analysis of New Physics contributions.

1. Introduction

We are in the year following the momentous announcement of experimental evidence for D^0 - \bar{D}^0 mixing [1, 2, 3, 4].¹ The time elapsed from the discovery of the charm degree of freedom was long (more than thirty years). From my own perspective, things really began to take off on the experimental side with the large fixed target experiments E687 and E791 in the 1990’s. Then the announcement by FOCUS of a much larger than expected width difference ($y_{CP} \sim 3.4\%$) created a buzz in the field. Finally in 2007 we saw the positive results of the B-factory experiments BaBar and Belle (followed by CDF). In the next Section, I review the latest findings and discuss what lessons they teach us.

2. Current Status of Charm Mixing

Let us consider four points regarding the current experimental situation as summarized in Ref. [5].

1. *Experimental evidence for charm mixing has improved.* At the CHARM 2007 Workshop (Cornell University 8/5/07-8/8/07) the euphoria of the moment provoked me to point out [6] that in light of the Physical Review Letters criteria of ‘observation’ ($> 5\sigma$) or ‘evidence’ (3σ -to- 5σ), the then-existing 2.4σ determination of x_D amounted to merely a ‘measurement’ ($< 3\sigma$). The current values (for the ‘no CP-violation’ fit)

$$\begin{aligned} x_D &\equiv \frac{\Delta M_D}{\Gamma_D} = 0.98_{-0.27}^{+0.26} \% \\ y_D &\equiv \frac{\Delta\Gamma_D}{2\Gamma_D} = (0.75 \pm 0.18) \% \end{aligned} \quad (1)$$

are at the level of ‘evidence’, and indeed in a plot of y_D vs x_D , the point $y_D = x_D = 0$ is excluded by 6.7σ [5].

2. *The current data set contains no evidence for CP-violation (hereafter CPV) in charm mixing.* We will consider the corresponding situation for charm decays in Sect. IV.
3. *Weeding out theoretical descriptions:* Due to the heretofore uncertain status of charm mixing, I have been reluctant to discard various theoretical descriptions. However, in view of the 95% C.L. values in the CPV-allowed fit to charm mixing, $0.39 \rightarrow 1.48$ for x_D (%) and $0.41 \rightarrow 1.13$ for y_D (%), I now feel that models having $y_D, x_D \sim 0.1\%$ are no longer tenable.
4. *The strong phase δ is not ‘very large’.* The no-CPV determination yields $\delta(^{\circ}) = 21.6_{-12.6}^{+11.6}$ whereas in the CPV-allowed fit the 95% C.L. values are $-6.3 \rightarrow 44.6$ for $\delta(^{\circ})$. This developing topic is detailed in the following subsection.

2.1. The Strong Phase

In the field of charm mixing, the ‘strong phase’ is defined as the relative phase between the $D^0 \rightarrow K^+\pi^-$ and $D^0 \rightarrow K^-\pi^+$ decay amplitudes. It appears in wrong-sign D^0 transitions because the $K^+\pi^-$ final state occurs both via doubly Cabibbo suppressed (DCS) decays and D^0 mixing followed by a Cabibbo favored (CF) decay. As a consequence, the parameters

$$\begin{aligned} x'_D &\equiv x_D \cos \delta + y_D \sin \delta \\ y'_D &\equiv y_D \cos \delta - x_D \sin \delta \end{aligned} \quad (2)$$

appear in the analysis. In the world of flavor SU(3) invariance, one has $\delta = 0$.

There is no way to completely avoid the presence of δ . For example, the time dependent rate for wrong-sign events in D^0 decay,

$$R\left(\frac{t}{\tau}\right) = R_D + \sqrt{R_D} y'_D \frac{t}{\tau} + \frac{x_D'^2 + y_D'^2}{4} \frac{t^2}{\tau^2}, \quad (3)$$

depends explicitly on x'_D and y'_D . There is no fundamental physics in δ ; it is a detail of the strong interac-

¹Throughout the talk I will often refer to D^0 - \bar{D}^0 mixing as

more specifically of charm mixing), it is an irritant, a nuisance.

Let me briefly review two rather different theoretical attempts to determine δ . Although neither is a first-principles application of QCD, both are well thought-out calculations.

1. *Nearby Resonances:* In Ref. [7], the CF and DCS amplitudes, respectively called A and B , are each expressed as a sum of tree and resonance contributions. The latter involves the weak transition of the initial D^0 into a resonance K^* whose mass is nearby that of the D^0 [8]. The K^* propagates and then decays strongly into the final state. The relative phase between tree and resonance components arises from the phase ϕ of the K^* propagator,

$$\tan \phi = -\frac{\Gamma_{K^*} M_D}{M_D^2 - M_{K^*}^2} . \quad (4)$$

Straightforward algebra then relates the strong phase δ to the resonance phase ϕ . In view of the vanishing of δ in the SU(3) limit, it is convenient to plot $\sin \delta$ as a function of an SU(3)-breaking parameter R_{exp} ,

$$R_{\text{exp}} \equiv \frac{\mathcal{B}_{D^0 \rightarrow K^+ \pi^-}}{\mathcal{B}_{\bar{D}^0 \rightarrow K^+ \pi^-}} \cdot \left| \frac{V_{ud} V_{cs}}{V_{us} V_{cd}} \right|^2 . \quad (5)$$

At the time Ref. [7] was written, one had $R_{\text{exp}}^{(1999)} = 1.58 \pm 0.49$. This led to speculation among some that δ was quite large, although the large uncertainty in R_{exp} allows no such conclusion. A more recent evaluation gives $R_{\text{exp}}^{(2008)} \simeq 1.2 \pm 0.04$. The uncertainty is now rather smaller and so is the central value.

2. *Phenomenological $D \rightarrow K\pi$ Analysis:* In Ref. [9], a study of seven CF and DCS $D \rightarrow K\pi$ modes is carried out in a model based on a traditional factorization and quark diagram approach. SU(3) breaking is incorporated largely via the decay constants f_K and f_π . A formula for $\cos \delta$ is derived in terms of the branching ratios $\mathcal{B}_{\bar{D}^0 \rightarrow K^- \pi^+}$, $\mathcal{B}_{\bar{D}^0 \rightarrow K^+ \pi^-}$ and $\mathcal{B}_{\bar{D}^+ \rightarrow K^+ \pi^0}$.

From the above two models, we should not be surprised to find $|\delta| \leq 20^\circ$ (both approaches predict only the magnitude $|\delta|$). In other words, the strong phase is not expected to be ‘very large’, a result in accord with the phenomenological analysis of Ref. [10] (whose determination gives a result consistent with zero).

There has been recent progress in measuring δ experimentally. Consider the reaction chain [11]

$$e^+ e^- \rightarrow \psi(3770) \rightarrow D^0 \bar{D}^0 \rightarrow ij , \quad (6)$$

where ij refers to some final state. The $D^0 \bar{D}^0$ pair will have $\mathcal{C} = \mathcal{P} = -1$. Define the CP eigenstates

The approach under discussion has the two remarkable features of emphasizing quantum correlations and of directly involving the CP-eigenstates. The transition rate for producing the final state ij obeys

$$\begin{aligned} \Gamma(i, j) &\propto |\langle i|D^0\rangle\langle j|\bar{D}^0\rangle - \langle j|D^0\rangle\langle i|\bar{D}^0\rangle|^2 \\ &= |\langle i|D_2\rangle\langle j|D_1\rangle - \langle j|D_2\rangle\langle i|D_1\rangle|^2 . \end{aligned} \quad (8)$$

The minus sign (since $\mathcal{C} = -1$) in the first of the rate equations is due to the quantum nature of the process and the second of the rate equations exhibits the explicit presence of the CP-eigenstates $D_{1,2}$. Not all final states ij are optimal for determining the strong phase. It is best to choose one of the final states as a CP eigenstate S_\pm and the other a $K\pi$ pair, *e.g.* as in

$$\begin{aligned} F_{S_\pm/K\pi}^{\text{corr}} &= |\langle S_\pm|D_2\rangle\langle K^-\pi^+|D_1\rangle|^2 \\ &= A_{S_\pm}^2 A_{K^-\pi^+}^2 |1 + re^{-i\delta}|^2 \end{aligned} \quad (9)$$

where the dependence on δ is explicit. Measurements based on this approach are presented in Refs. [12, 13], which give $\cos \delta = 1.03 \pm 0.31 \pm 0.06$. By further including external measurements of charm mixing parameters, an alternate measurement of $\cos \delta$ is obtained, yielding $\delta = (22_{-12}^{+11})^\circ$. Presumably, future experimental studies will be able to reduce present uncertainties, *e.g.* for a discussion of measuring the strong phase at BES-III see Ref. [14].

3. The Origin of Charm Mixing

In principle, charm mixing can arise from the Standard Model (SM) and/or from New Physics (NP). We shall cover both in this talk, but consider the NP possibility in greater detail.

3.1. Standard Model

Theoretical estimates of charm mixing have been performed using either quark or hadron degrees of freedom. We shall discuss each of these in turn.

3.1.1. Quark Degrees of Freedom

To my knowledge, the earliest attempt of this type is contained in Ref. [15]. These days, the usual approach (like that used in $B_{d,s}$ mixing) is to express the mixing matrix element as a sum of local operators ordered according to dimension (operator product expansion or simply OPE) [16]. At a given order in the OPE, the mixing amplitude is expanded in QCD perturbation theory. Finally matrix elements of the various local operators are determined. It is a peculiarity of charm mixing that the various mixing amplitudes are most conveniently characterized by expanding in

A full implementation of this program is daunting because the number of local operators increases sharply with the operator dimension D (e.g. $D = 6$ has two operators, $D = 9$ has fifteen, and so on) [17]. The matrix elements of the various local operators are unknown and can be only roughly approximated in model calculations. In principle, QCD lattice determinations would be of great use, but they are not generally available at this time [18].

An analysis of x_D and y_D in the leading order $D = 6$ in the OPE has been carried out through $\mathcal{O}(\alpha_s)$ in Ref. [19]. The result through $\mathcal{O}(\alpha_s)$ is $x_D \simeq y_D \sim 10^{-6}$. These small values are due in part to severe flavor cancellations (the leading terms in the z -expansion for x_D and y_D respectively are z^2 and z^3 at order α_s^0 and z^2 and z^3 at order α_s^1).

Evidently, the quark approach as implemented via the OPE has been seen as *not* the way to understand charm mixing. It involves a triple expansion (in operator dimension D , QCD coupling α_s and parameter z) which is at best slowly convergent. One long-standing beacon of hope has been the suggestion in Ref. [20] that six-quark operators whose Wilson coefficients suffer only one power of z suppression might give rise to $x_D \sim 0.1\%$. Even this effect (whose estimated size is problematic due to uncertainties in matrix element evaluation) is too small.

3.1.2. Hadronic Degrees of Freedom

Let us restrict our attention to the following exact relation for the width difference $\Delta\Gamma_D = \text{Im} I/M_D$ where

$$I \equiv \langle \bar{D}^0 | i \int d^4x T \left\{ \mathcal{H}_w^{|\Delta C|=1}(x) \mathcal{H}_w^{|\Delta C|=1}(0) \right\} | D^0 \rangle. \quad (10)$$

We can calculate y_D by inserting intermediate states between the $|\Delta C| = 1$ weak hamiltonian densities $\mathcal{H}_w^{|\Delta C|=1}$. Of course, knowledge of the matrix elements $\langle n | \mathcal{H}_w^{|\Delta C|=1} | D^0 \rangle$ is required. This method yielded an entirely reasonable estimate for y_{B_s} , where the number of large matrix elements turns out to be quite limited [21].

By contrast, for charm mixing the number of contributing matrix elements is quite large. Perhaps the most comprehensive analysis to date for charm is the phenomenological evaluation based on factorization given in Ref. [22]. The result $y_D \sim 0.1\%$ thus obtained is too small.

This unfortunate circumstance shows how delicate this sum over many contributions seems to be. What then is one to do, given that the hadron approach appears tied to the issue of matrix element evaluation? Perhaps it is best to rely more on charm decay data and less on the underlying theory. The earliest work of this type [23, 24] focussed on the

states in Eq. (10). In the flavor SU(3) limit, exact cancellations reduce the contribution from this subset of states to zero. However, SU(3) breaking was already known to be significant in individual charm decays, and based on data available at that time, these references concluded that ‘ y_D might be large’.

A modern version of this approach exists [25], but with the above argument essentially turned on its head. A main new ingredient is the realization that SU(3) breaking occurs at second order in charm mixing [26]. Can it be that all two-particle and three-particle sectors (such as P^+P^-) contribute very little to charm mixing due to flavor cancellations? Perhaps, but this argument cannot be continued to the four-particle intermediate states because decay into four-kaon states is kinematically forbidden. In fact, Ref. [25] claims that these very sectors can generate $y_D \sim 10^{-2}$. A dispersion relation calculation using charm decay widths as input can be used to estimate x_D , but this contains an additional layer of model dependence.

I believe the claim that SM contributions produce values for x_D and y_D at the 1% level is not unreasonable. At the same time, however, compared to SM predictions for kaon, B_d and B_s mixing, the status of charm mixing is decidedly ‘fuzzy’.

3.2. New Physics

The LHC era is about to begin. Yet, what we will learn from LHC data is still highly uncertain. This is in stark contrast with SM expectations at the time LEP came on line. Our own recent work on x_D has tried to be bias-free by allowing for a variety of extensions to the Standard Model [27],

- 1] Extra gauge bosons (LR models, *etc*)
- 2] Extra scalars (multi-Higgs models, *etc*)
- 3] Extra fermions (little Higgs models, *etc*)
- 4] Extra dimensions (split fermion models, *etc*)
- 5] Extra global symmetries (SUSY, *etc*).

NP contributions to charm mixing can affect y_D as

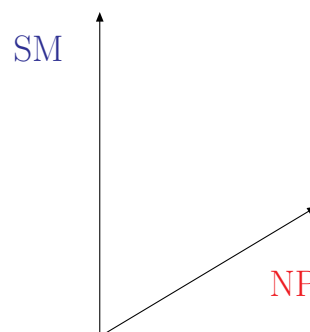


Figure 1: Possibility of SM and NP Contributions

well as x_D . We do not consider the former in this talk, but instead refer the reader to Refs. [28, 29].

The strategy for calculating the effect of NP on D^0 mixing is, for the most part, straightforward. One considers a particular NP model and calculates the mixing amplitude for as a function of the model parameters. If the mixing signal is sufficiently large, constraints on the parameters are obtained. For all we know, the observed D^0 mixing signal is a product of both SM *and* NP contributions. In general we will not know the relative phase between the SM and NP amplitudes, as depicted in Fig. 1, or even the precise value of the ‘fuzzy’ SM component. This affects how NP constraints are treated, as shown later in a specific example.

We now turn to the issue of NP and x_D , as based on the work in Ref. [27], which studied a total of 21 NP models. These are listed in Table I.

Of these 21 NP models, only four (split SUSY, universal extra dimensions, left-right symmetric and flavor-changing two-higgs doublet) are ineffective in producing charm mixing at the observed level. This has several causes, *e.g.* the NP mass scale is too large, severe cancellations occur in the mixing signal, *etc.* This means that 17 of the NP models *can* produce charm mixing. For these, we can get constraints on masses and mixing parameters.

Table I NP models studied in Ref. [27]

Model
Fourth Generation
$Q = -1/3$ Singlet Quark
$Q = +2/3$ Singlet Quark
Little Higgs
Generic Z'
Family Symmetries
Left-Right Symmetric
Alternate Left-Right Symmetric
Vector Leptoquark Bosons
Flavor Conserving Two-Higgs-Doublet
Flavor Changing Neutral Higgs
FC Neutral Higgs (Cheng-Sher ansatz)
Scalar Leptoquark Bosons
Higgsless
Universal Extra Dimensions
Split Fermion
Warped Geometries
Minimal Supersymmetric Standard
Supersymmetric Alignment
Supersymmetry with RPV
Split Supersymmetry

3.2.1. R_P Violations and D^0 Mixing

We cannot review all 17 NP models here, so we shall concentrate on just one of them, the case of R-parity violating (RPV) supersymmetry. RPV contributes to D^0 mixing via box amplitudes, as displayed in Fig. 2. Each box diagram is seen to contain four vertices in which quarks, squarks and leptons interact.

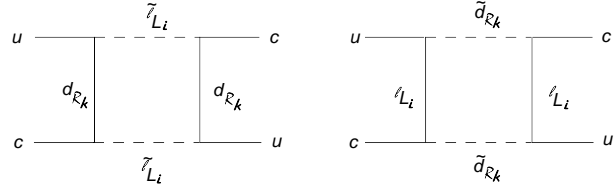


Figure 2: RPV box diagram.

Fig. 3 provides a brief summary about this topic. The quantum number R_P distinguishes between particles of the SM and their supersymmetric partners (‘sparticles’). R-parity need not be conserved and in Fig. 3 we display an R_P -violating lagrangian that is relevant to charm-mixing. The coupling strength is $\tilde{\lambda}'_{ijk}$ and the indices $i, j, k = 1, 2, 3$ are generation labels. The amplitude for $c \rightarrow u\ell^+\ell^-$ appearing in Fig. 3 is part of the box-diagram which mediates the charm mixing. Note that it is proportional to the product $\tilde{\lambda}'_{i1k} \tilde{\lambda}'_{i2k}$. Incidentally, to an experimentalist who has dealt with lepton-antilepton pairs, this amplitude has the unexpected feature that the pair come from distinct vertices and not from a photon or a Z^0 .

R_P VIOLATING SUSY

Introduce RPV Interaction $\mathcal{L}_{\tilde{\lambda}'}$

$$R_P = (-)^{3(B-L)+2S} = \begin{cases} +1 & \text{(particle)} \\ -1 & \text{(sparticle)} \end{cases}$$

$$\mathcal{L}_{\tilde{\lambda}'} = \tilde{\lambda}'_{ijk} [-\tilde{e}_L^i \tilde{d}_R^k u_L^j - \tilde{u}_L^i \tilde{d}_R^k e_L^j - (\tilde{d}_R^k)^* (\tilde{e}_L^i)^c u_L^j + \dots]$$

Constrain the $\{\tilde{\lambda}'_{ijk}\}$ via data (i, j, k generation labels).

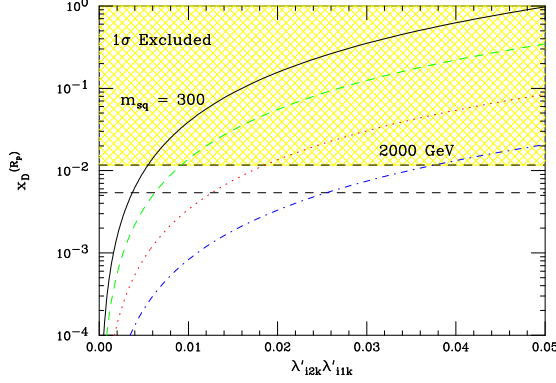
Example: $c \rightarrow u\ell^+\ell^-$

Tree-level non-electromagnetic process!

Mediated by exchange of down squark \tilde{d} .

Effect proportional to $\tilde{\lambda}'_{i1k} \cdot \tilde{\lambda}'_{i2k}$.

Figure 3: Outline of R_P -violation in SUSY


 Figure 4: Constraints on RPV from D^0 mixing.

We refer the reader to Ref. [27] for details regarding the calculation of the RPV contributions to D^0 mixing. The end result of the analysis is the set of constraints displayed in Fig. 4. There, x_D is plotted as a function of the product of the RPV couplings $\tilde{\lambda}'_{i2k}\tilde{\lambda}'_{i1k}$. We take $m_{\tilde{d}_{R,k}} = m_{\tilde{\ell}_{L,i}}$, with $m_{\tilde{d}_{R,k}} = 300, 500, 1000$ and 2000 GeV corresponding to the solid, green dashed, red dotted, and blue dashed-dotted curves, respectively. The 1σ experimental bounds are as indicated, with the yellow shaded region depicting the region that is excluded. The bound cited in Ref. [27] for the RPV couplings is

$$\tilde{\lambda}'_{i2k}\tilde{\lambda}'_{i1k} \leq 0.085\sqrt{x_D^{(\text{expt})}} \left(\frac{m_{\tilde{d}_{R,k}}}{500 \text{ GeV}} \right) \quad (11)$$

or using the updated mixing value of Eq. (1) we find

$$\tilde{\lambda}'_{i2k}\tilde{\lambda}'_{i1k} \leq 1.7 \cdot 10^{-3} m_{\tilde{d}_{R,k}}/100 \text{ GeV} \quad (12)$$

3.2.2. The Rare Decay $D^0 \rightarrow \mu^+\mu^-$

It is often profitable for phenomenological studies to encompass various physical processes at the same time. The following is a case in point. It should be clear that the squark-exchange diagram at the bottom of Fig. 3 contributes not only to vertices in the D^0 mixing amplitude but also to rare transitions such as $D^0 \rightarrow \mu^+\mu^-$, $D^0 \rightarrow \pi^+\mu^+\mu^-$, etc [30]. In fact, the current experimental limit [31]

$$\mathcal{B}_{D^0 \rightarrow \mu^+\mu^-} \leq 1.3 \cdot 10^{-6}$$

implies the constraint

$$\tilde{\lambda}'_{21k}\tilde{\lambda}'_{22k} \leq 7 \cdot 10^{-3} m_{\tilde{d}_{R,k}}/100 \text{ GeV} \quad (13)$$

This illustrates how charm mixing and charm rare decays are both of interest to RPV phenomenology. They are roughly competitive at present. However, the limit from charm is not going to change much whereas that from $D^0 \rightarrow \mu^+\mu^-$ can continue to im-

4. CPV Asymmetries

Since there is no existing evidence for CPV in the charm sector, it is natural to look to the future. We consider two topics of this type, first, possible experimental strategies for detecting CPV signals and next, a survey of NP models and their CPV asymmetries. For existing literature on the subject, I recommend a recent discussion by Petrov [32] and a treatment of basic CPV formalism applied to charm by Xing [33].

4.1. Future Strategies

I briefly review two papers, each involving a facility planned for future operation.

1. *Super B-factory*: A suggestion for work at a super B-factory is to probe charm mixing and CPV using coherent $D^0\bar{D}^0$ events from $\Upsilon(1S)$ decays [34]. The point is that the large boost factor in the $\Upsilon(1S)$ rest frame ($\simeq 2.33$) would allow a precise determination of the proper time interval τ between the two D decays. Thus for a final state f_1f_2 , one would measure

$$R(f_1, f_2; t) = \frac{d\Gamma_{\Upsilon(1S) \rightarrow f_1 f_2}}{d\tau} \quad (14)$$

Symmetric and asymmetric $\Upsilon(1S)$ factories are considered and various CPV asymmetries discussed. A yield of $10^7 \rightarrow 10^8$ D-pairs per year is estimated.

2. τ -Charm Factory: Ref. [35] considers the decay modes $D \rightarrow K^*K$ obtained by running on the $\psi(3770)$ and $\psi(4140)$ resonances at a τ -Charm factory. Note that the C-parity values differ for these two states, with $\mathcal{C}[\psi(3770)] = -1$ and $\mathcal{C}[\psi(4140)] = +1$. The production of final states for such experiments would be coherent, and one defines the quantities

$$\begin{aligned} \Gamma_c^{++} &\equiv \Gamma(K^{*+}K^-, K^{*+}K^-)_c \\ \Gamma_c^{--} &\equiv \Gamma(K^{*-}K^+, K^{*-}K^+)_c \\ \Gamma_c^{+-} &\equiv \Gamma(K^{*+}K^-, K^{*-}K^+)_c \\ \Gamma_c^{-+} &\equiv \Gamma(K^{*-}K^+, K^{*+}K^-)_c \end{aligned} \quad (15)$$

The authors conclude that it is favorable to measure decays of correlated D 's the various K^*K states by running on the $\psi(4140)$, with a candidate CPV observable being $(\Gamma_{++}^{+-} - \Gamma_{+-}^{+-})/\Gamma_{+-}^{+-}$.

4.2. Calculating CPV Asymmetries

An interesting analysis of CP-violations in the singly-Cabibbo-suppressed transitions

as recently been carried out in Ref. [36]. Final states which are both CP eigenstates (K^+K^- , $\pi^+\pi^-$, etc) and non-CP eigenstates (K^*K , $\rho\pi$, etc) are considered.

Let us restrict our attention to the time-integrated CPV asymmetries of a final state f which is a CP eigenstate ($\bar{f} = f$),

$$a_f \equiv \frac{\Gamma_{D^0 \rightarrow f} - \Gamma_{\bar{D}^0 \rightarrow f}}{\Gamma_{D^0 \rightarrow f} + \Gamma_{\bar{D}^0 \rightarrow f}} . \quad (16)$$

Such an asymmetry can receive contributions from decay, mixing and interference,

$$a_f = a_f^d + a_f^m + a_f^i . \quad (17)$$

The ‘direct’ component (*i.e.* from decay) is generally expressed as

$$a_f^d = 2r_f \sin \phi_f \sin \delta_f , \quad (18)$$

where the phases ϕ_f and $\sin \delta_f$ arise respectively from CPV and QCD.

What are the experimental prospects for measuring such CPV asymmetries? There can, in principle, be both SM and NP components. As with charm mixing, there can be both short-distance and long-distance SM contributions, with the latter subject to less suppression than the former. However, due to uncertainties in estimating the long-distance component it is hard to be very precise about the actual size of SM asymmetries. At any rate, it is concluded in Ref. [36] that the SM cannot generate CPV asymmetries in the SCS sector much larger than $\mathcal{O}(10^{-4})$.

At the time at which the work of Ref. [36] was carried out, the scale of experimental limits on the CPV asymmetries was roughly $\mathcal{O}(10^{-2})$. This would appear to present a wide window of opportunity for observation of NP effects. However, some up-to-date (as of 1/31/08) experimental limits from the Charm Heavy Flavor Averaging Group [37] are exhibited in Table II. In arranging this Table, I selected only those limits whose uncertainties are less than 0.01. We see that the window is not as large today!

Table II Current CPV Asymmetry Data

Asymmetry	Mode	Value
$\Delta\Gamma/2\Gamma$	$D^0 \rightarrow K^+K^-$	0.0015 ± 0.0034
	$D^0 \rightarrow \pi^+\pi^-$	0.0002 ± 0.0051
	$D^0 \rightarrow K^-\pi^+\pi^0$	0.0016 ± 0.0089
	$D^+ \rightarrow K_S\pi^+$	0.0086 ± 0.009
	$D^+ \rightarrow K^+K^-\pi^+$	0.0059 ± 0.0075
$\Delta\tau/2\tau$	$D^0 \rightarrow K^+K^-, \pi^+\pi^-$	0.0012 ± 0.0025

I leave it to the reader to study the various technical details present in Ref. [36]. However, some general

1. Some supersymmetric models can give $a_f^d \sim \mathcal{O}(10^{-2})$ whereas models with minimal flavor violation cannot.
2. Only the SCS decays probe gluonic penguin amplitudes. Thus any large CPV asymmetries arising from this source would be unlikely for CF and DCS decays.
3. CPV asymmetries as large as $a_f^d \sim \mathcal{O}(10^{-2})$ would be expected from NP theories which contribute via loop amplitudes but not tree amplitudes (tree amplitudes tend to be constrained by D^0 mixing constraints).

5. Conclusions

As we enter the LHC era, our field will require the resources to pursue both *discovery* and *precision* options. The discovery option will be carried out at the LHC. If, as anticipated, New Physics is revealed, perhaps (i) the signature will be so striking that a specific NP model is clearly identified, or (ii) the situation will be unclear for quite some time (*e.g.* some of the NP degrees of freedom might remain beyond the LHC reach). In either case, it will be important to carry out the precision option. For the case (i) above, we need to check and verify the LHC results, whereas for case (ii) observing the pattern of rare effects should help clarify the LHC findings. This will require the participation of LHC-B and e^+e^- super-flavor factories. How many such facilities will become operable only time will tell. One can only hope. Now onto a summary of the main topics:

Charm mixing and experiment:

The data on D^0 mixing allow us at long last to claim (in the sense of PRL discovery criteria) ‘evidence’ for determinations of x_D & y_D and a true ‘observation’ of mixing. The quality of the mixing signal now can rule out theoretical descriptions predicting charm mixing at the 0.1% level. There has been real progress on the issue of the strong phase difference δ between the $D^0 \rightarrow K^-\pi^+$ and $D^0 \rightarrow K^+\pi^-$ amplitudes. We expect that improved sensitivity in the quantum correlation approach will provide a more accurate measure of δ .

Charm mixing and Standard Model theory:

There is little change in our previous understanding of this subject. The quark approach which is carried out in the OPE has, to date, yielded $x_D, y_D \sim 10^{-6}$. Even the most optimistic prediction for using this method predicts a mixing signal an order of magnitude too small. We have here a very slowly convergent process which nobody has yet been able to conquer. More promising is the hadron approach which might

hampered by theoretical uncertainties. Nonetheless, we are still able to conclude that the observed D^0 mixing might well be a consequence of SM physics.

Charm mixing and New Physics theory:

The comprehensive study in Ref. [27] of 21 possible NP contributions to charm mixing shows that the observed D^0 mixing might also well be a consequence of beyond-SM physics! Further progress on this front will presumably require input from LHC data for selecting among NP possibilities. We have pointed out how the inter-related phenomenologies of charm mixing and rare charm decays allows for a more systematic probe of NP parameter spaces.

Studies involving CP-violations in charm:

With the observation of charm mixing, the study of CP-violations in charm has taken its place at the forefront of research in this field. Given the expectation that CP-violating SM asymmetries should be less than $\mathcal{O}(10^{-3})$ and that some NP models can exceed this value, there should be a real window of opportunity to aim at. However, this window has begun to close. One is left wondering as usual – where is the New Physics?

Acknowledgments

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References

- [1] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **98**, 211802 (2007) [arXiv:hep-ex/0703020].
- [2] M. Staric *et al.* [Belle Collaboration], Phys. Rev. Lett. **98**, 211803 (2007) [arXiv:hep-ex/0703036].
- [3] K. Abe *et al.* [BELLE Collaboration], Phys. Rev. Lett. **99**, 131803 (2007) [arXiv:0704.1000 [hep-ex]].
- [4] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **100**, 121802 (2008) [arXiv:0712.1567 [hep-ex]].
- [5] A. J. Schwartz, arXiv:0803.0082v2 [hep-ex].
- [6] E. Golowich, *In the Proceedings of International Workshop on Charm Physics (Charm 2007), Ithaca, New York, 5-8 Aug 2007, pp 05* [arXiv:0710.0151 [hep-ph]].
- [7] A. F. Falk, Y. Nir and A. A. Petrov, JHEP **9912**,
- [8] For a model of charm mixing based on ‘nearby resonances’, see E. Golowich and A. A. Petrov, Phys. Lett. B **427**, 172 (1998) [arXiv:hep-ph/9802291].
- [9] D. N. Gao, Phys. Lett. B **645**, 59 (2007) [arXiv:hep-ph/0610389].
- [10] Q. He *et al.* [CLEO Collaboration], Phys. Rev. Lett. **100**, 091801 (2008) [arXiv:0711.1463 [hep-ex]].
- [11] D. M. Asner and W. M. Sun, Phys. Rev. D **73**, 034024 (2006) [Erratum-ibid. D **77**, 019902 (2008)] [arXiv:hep-ph/0507238].
- [12] D. M. Asner *et al.* [CLEO Collaboration], arXiv:0802.2268 [hep-ex].
- [13] J. L. Rosner *et al.* [CLEO Collaboration], arXiv:0802.2264 [hep-ex].
- [14] X. D. Cheng, K. L. He, H. B. Li, Y. F. Wang and M. Z. Yang, Phys. Rev. D **75**, 094019 (2007) [arXiv:0704.0120 [hep-ex]].
- [15] A. Datta and D. Kumbhakar, Z. Phys. C **27**, 515 (1985).
- [16] H. Georgi, Phys. Lett. B **297**, 353 (1992) [arXiv:hep-ph/9209291].
- [17] For interesting work on the problem of higher operator dimensions, see T. Ohl, G. Ricciardi and E. H. Simmons, Nucl. Phys. B **403**, 605 (1993) [arXiv:hep-ph/9301212].
- [18] However, see R. Gupta, T. Bhattacharya and S. R. Sharpe, Phys. Rev. D **55**, 4036 (1997) [arXiv:hep-lat/9611023].
- [19] E. Golowich and A. A. Petrov, Phys. Lett. B **625**, 53 (2005) [arXiv:hep-ph/0506185].
- [20] I.I.Y. Bigi and N.G. Uraltsev, Nucl. Phys. B **592**, 92 (2001) [arXiv:hep-ph/0005089].
- [21] R. Aleksan, A. Le Yaouanc, L. Oliver, O. Pene and J. C. Raynal, Phys. Lett. B **316**, 567 (1993).
- [22] F. Buccella, M. Lusignoli, G. Miele, A. Pugliese and P. Santorelli, Phys. Rev. D **51**, 3478 (1995) [arXiv:hep-ph/9411286].
- [23] J.F. Donoghue, E. Golowich, B.R. Holstein and J. Trampetic, Phys. Rev. D **33**, 179 (1986).
- [24] L. Wolfenstein, Phys. Lett. B **164**, 170 (1985).
- [25] A.F. Falk, Y. Grossman, Z. Ligeti, Y. Nir and A.A. Petrov, Phys. Rev. D **69**, 114021 (2004) [arXiv:hep-ph/0402204].
- [26] A.F. Falk, Y. Grossman, Z. Ligeti and A.A. Petrov, Phys. Rev. D **65**, 054034 (2002) [arXiv:hep-ph/0110317].
- [27] E. Golowich, J. Hewett, S. Pakvasa and A. A. Petrov, Phys. Rev. D **76**, 095009 (2007) [arXiv:0705.3650 [hep-ph]].
- [28] E. Golowich, S. Pakvasa and A. A. Petrov, Phys. Rev. Lett. **98**, 181801 (2007) [arXiv:hep-ph/0610039].
- [29] A. A. Petrov and G. K. Yeghiyan, Phys. Rev. D **77**, 034018 (2008) [arXiv:0710.4939 [hep-ph]].
- [30] G. Burdman, E. Golowich, J. L. Hewett and S. Pakvasa, Phys. Rev. D **66**, 014002 (2002)

- [arXiv:hep-ph/0112235].
- [31] W. M. Yao *et al.* [Particle Data Group], *J. Phys. G* **33** (2006) 1.
- [32] A. A. Petrov, *In the Proceedings of International Workshop on Charm Physics (Charm 2007), Ithaca, New York, 5-8 Aug 2007, pp 11* [arXiv:0711.1564 [hep-ph]].
- [33] Z. z. Xing, *Phys. Rev. D* **55**, 196 (1997) [arXiv:hep-ph/9606422].
- [34] H. B. Li and M. Z. Yang, *Phys. Rev. D* **74**, 094016 (2006) [arXiv:hep-ph/0610073].
- [35] Z. z. Xing and S. Zhou, *Phys. Rev. D* **75**, 114006 (2007) [arXiv:0704.0971 [hep-ph]].
- [36] Y. Grossman, A. L. Kagan and Y. Nir, *Phys. Rev. D* **75**, 036008 (2007) [arXiv:hep-ph/0609178].
- [37] See the website
<http://www.slac.stanford.edu/xorg/hfag/charm>.