$D^o\bar{D}^o$ Mixing and CP Violation in D Decays –

Can There Be High Impact Physics in Charm Decays?*

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Abstract of the Abstract:

There certainly can be!

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The phenomenology of D^o-$\bar{D}^0$ mixing and of CP violation in D decays is described. Semi-quantitative predictions based on the Standard Model are given on the possible strength of these phenomena. It is pointed out that New Physics beyond the Standard Model would probably enhance these phenomena in quite a significant way. To justify a New Initiative one has to be able to probe D^o-$\bar{D}^0$ mixing down to $r_D = 10^{-4}$ (or better) and CP asymmetries down to 1 % (or better). It is of obvious benefit for such searches if one is able to track the proper time evolution of these decays by locating the decay vertices. Yet this can hardly be achieved if one uses e^+e^- annihilation operating in the charm threshold region. It is discussed in some detail how the same kind of dynamical information can be obtained even without visible decay vertices, namely by employing $D\bar{D}$ decay correlations in a judicious fashion.

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I. Executive Summary

Since I do not want to leave the reader unduly in the dark about my opinions on the subject matter, I will start off by giving an executive summary:

(i) Yes, H.I.P., i.e. High Impact Physics can emerge in charm decays.

(ii) A dedicated effort to search for it is more than justified – it is called for!

(iii) Such a search can be performed in several different experimental environments; their relative strengths have to be evaluated in a detailed way. This has not been done yet for most of these environments. However, it will be seen that a high luminosity e^+e^- machine operating in the threshold region for charm production provides the necessary tools for accepting this challenge, namely to search for High Impact Physics.

In the following, I will discuss $D^o\overline{D}^o$ mixing and CP violation; in each case I will present first the relevant phenomenology and then sketch theoretical expectations on the size of the various phenomena.

II. $D^o\overline{D}^o$ Mixing

A. Phenomenology

(1) Fundamentals

Mixing means that the two flavour eigenstates – D^o and $\overline{D}^o$ – are different from the two mass eigenstates; the latter are characterized by a mass splitting – Δm – and a difference in width – $\Delta\Gamma$. For our subsequent discussion it is convenient to introduce the dimensionless quantities

$$x = \frac{\Delta m}{\Gamma}, \ y = \frac{\Delta \Gamma}{2\Gamma} \tag{1}$$

Accordingly the decay of a meson that was produced as a flavour eigenstate, say a D^o, will exhibit an evolution in (proper) time that is *not purely exponential*. This is the *primary* signature of $D^o\overline{D}^o$ (or $B^o\overline{B}^o$ etc.) mixing. More specifically one finds for decays into a final state f

$$\text{rate}\,(D^o(t) \rightarrow f) \propto e^{-\Gamma t}\left\{A_f + y\frac{t}{\tau_D}B_f + \frac{x^2+y^2}{2}\left(\frac{t}{\tau_D}\right)^2\right\} \tag{2}$$

where we have used x, y << 1 as inferred from the present experimental bounds on mixing; for the time being we have also assumed CP invariance. The quantities A_f and B_f do *not* depend on the time t and are *specific* to the final state f; A_f denotes the direct decay and B_f the interference between the direct decay and the mixing process.

In the following I will concentrate on two specific decay modes, namely the semi-leptonic reactions $D^o \to l^- X$ vs. $D^o \to l^+ X$ and the non-leptonic transitions $D^o \to K^+\pi^-$ vs. $D^o \to K^-\pi^+$. These examples compliment each other and already allow to illustrate the full width of the relevant phenomenology.

For semi-leptonic decays the expression (2) gets simplified considerably since

$$A_f = O = B_f \quad \text{for} \quad f = l^- X$$

at least in the Standard Model :

$$\text{rate}\left(D^o(t) \to \ell^- X\right) \propto e^{-\Gamma t}\left(\frac{t}{\tau_D}\right)^2 \frac{x^2+y^2}{2} \tag{3}$$

For the non-leptonic mode one obtains instead [1]

$$\text{rate}\ (D^o(t) \to K^+\pi^-) \propto$$
$$e^{-\Gamma t}\left\{2\ tg^4\theta_c\left|\hat{\rho}_{K\pi}\right|^2 + 2\ y\left(\frac{t}{\tau_D}\right) tg^2\theta_c\left|\hat{\rho}_{K\pi}\right| + \frac{x^2+y^2}{2}\left(\frac{t}{\tau_D}\right)\right\} \tag{4}$$

with

$$tg^2\theta_c\ \hat{\rho}_{K\pi} \equiv \frac{T(D^o \to K^+\pi^-)}{T(D^o \to K^-\pi^+)} = \frac{T(\bar{D}^o \to K^-\pi^+)}{T(\bar{D}^o \to K^+\pi^-)} \tag{5}$$

denoting the relative strength (in amplitude) of the doubly Cabibbo suppressed decay mode; furthermore *I have assumed CP invariance for the time being.*

From (3) and (4) one reads off directly two properties:

•• It is obviously quite advantageous if one can resolve the position of the D decay vertex relative to the production point; for this information would allow us to reconstruct the decay rate evolution in proper time.

•• In that case one obtains the cleanest signal for the largest value of t that is feasible statisticswise.

Integrating (3) over all times of decay one arrives at

$$r_D \equiv \frac{\text{Prob}\ (D^o \to \bar{D}^o \to \ell^- X)}{\text{Prob}\ (D^o \to \ell^+ X)} \cong \frac{x^2+y^2}{2} \tag{6}$$

A non-vanishing value for r_D is therefore a *secondary* signature for $D^o\bar{D}^o$ mixing, by which I mean the following: $D^o\bar{D}^o$ mixing generates $r_D \neq 0$ -- yet an observation of $r_D \neq 0$ per se establishes only that a certain selection rule is violated in processes where the charm quantum number is changed, namely the rule

$$\Delta\text{Charm} = - \Delta Q_l \qquad (7)$$

where Q_l denotes leptonic charge . This violation can occur with a *non-trivial* dependence on (proper) time as it is produced by $D^o\bar{D}^o$ *mixing*; or it could be *independent of time*, in which case it would be unambigously due to *physics beyond the Standard Model.* The relevance of such a distinction is demonstrated in $D^0 \to K^+\pi^-$ decays where doubly Cabibbo suppressed transitions contribute irrespective of $D^o\bar{D}^o$ mixing; they actually produce an annoying background since they are already present in the Standard Model.

There is also another reason why it would be quite imprudent to stake a claim on the observation of $D^o\bar{D}^o$ mixing on a single time integrated quantity like $D^0 \to l^-X$ vs. $D^0 \to l^+X$. It is admittedly a technical reason, yet nevertheless quite relevant. We already know that $D^o\bar{D}^o$ mixing does not proceed in a hasty manner: E691 has presented an upper bound [2]

$$r_D \leq 5 \times 10^{-3} \qquad (8)$$

To acquire a 10^{-3} sensitivity for r_D requires tight control over systematic uncertainties. I find it hard to believe that such a tight control can be demonstrated when one is dealing with a single time-integrated quantity. Thus it would appear that the ability to resolve D^o decay vertices directly on a routine basis constitutes not merely a helpful feature for future studies on $D^o\bar{D}^o$ mixing, but an indispensible one. In the following chapter I will show that such a sweeping statement is not generally correct since it overlooks a notable exception.

(2) "Trading time for space"

It hardly needs repeating that charm production near threshold in e^+e^- annihilation provides many experimental advantages. However it is very hard, if not even practically impossible, to resolve the positions of the D decay vertices in this special kinematical regime. Thus, at first sight, it would seem that searches for $D^o\bar{D}^o$ mixing in such an experimental scenario are severly limited in their scope . Longer reflection, however, shows that this pessimistic judgement is incorrect: quite on the contrary, charm production in an e^+e^- charm tau factory is well suited for highly sensitive searches for $D^o\bar{D}^o$ mixing if one analyzes the quantum mechanical aspects of the production process carefully.

An analogy with radioastronomy might help to illustrate the basic idea. Imagine you want to analyze the spatial structure of a far-away radio source. Yet there is no radio dish available that is large enough to resolve the radio source directly. Rather than giving up in your quest you employ a *second* radio dish and position it at a well defined distance L to the first dish. You then undertake a "run" (of 12 hours length in this case) where radio signals are recorded at *both* radio dishes with precise relative timing. Next you decrease the distance between the positions of the two dishes and undertake another run of data taking and so on and so forth. Covering the various space intervals from L down to zero allows you to reconstruct a picture of the radio source with a spatial resolution that corresponds to a single radio dish with diameter L albeit at the expense of a much longer time required for data taking. In that sense you have traded time (spent) for space (resolution acquired). The physical principle that underlies this tremendous gain in (space) resolution is that of iterative interferometry.

This same principle can be employed in charm production near threshold in e^+e^- annihilation [3] :

$$e^+e^- \to 1\gamma \to D^o\bar{D}^oX \tag{9}$$

The final state then is odd under charge conjugation C. If *at most* one π^o or γ is produced together with the $D^o\bar{D}^o$ pair, i.e.

$$X = \varnothing, \pi^o, \gamma \tag{10}$$

then the $D^o\bar{D}^o$ pair forms an eigenstate under C.

The $D^o\bar{D}^o$ pairs thus originate from a coherent quantum state; the two neutral D mesons possess well-defined relative phases which can be determined by observing the decays of *both* the D^o and $\bar{D}^o$. Studying the correlations in these D decays for C even and C odd then amounts to interferometry. It is actually irrelevant here whether the D^o and π^o or the D^o and γ come from a D^{*o} decay or not or at which energy the $D^o\bar{D}^o$ pair is produced.

More specifically one finds the following pattern in the ratio of like-sign to opposite-sign di-leptons when measuring semi-leptonic D^o decays [3]

$$\begin{array}{l} e^+ e^- \to D^o\bar{D}^o + \ldots \\ \quad\quad\;\; \lfloor\;\; \hookrightarrow l^\pm \ldots \\ \quad\quad\;\; \hookrightarrow l^\pm \ldots \end{array}$$

reaction	$\frac{\text{Number}(\ell^{\pm}\ell^{\pm})}{\text{Number}(\ell^{+}\ell^{-})}$	$C[D^o\bar{D}^o]$
i) $e^+e^- \to D^o\bar{D}^o$	r_D	-
ii) $e^+e^- \to D^o\bar{D}^{o*}$ + h.c. $\to D^o\bar{D}^o\gamma$	$3r_D$	+
iii) $e^+e^- \to D^o\bar{D}^{o*}$ + h.c. $\to D^o\bar{D}^o\pi^o$	r_D	-

Table 1

where the last column denotes the C parity of the $D^o\bar{D}^o$ pair.

A more complex pattern arises for the non-leptonic decays

$$e^+ e^- \to \underset{\displaystyle \hookrightarrow K^{\pm}\pi^{\mp}}{D^O}\,\underset{\displaystyle \hookrightarrow K^{\pm}\pi^{\mp}}{\bar{D}^O} + \ldots \tag{12}$$

since doubly Cabibbo suppressed D decays (hereafter referred to as DCSD) can produce like-sign kaons irrespective of $D^o\bar{D}^o$ mixing.

reaction	$\frac{\text{Number}((K^{\pm}\pi^{\mp})_D\,(K^{\pm}\pi^{\mp})_D)}{\text{Number}((K^{\pm}\pi^{\mp})_D\,(K^{\mp}\pi^{\pm})_D)}$	
	including mixing	without mixing
i. $e^+e^- \to D^o\bar{D}^o$	r_D	0 !
ii. $e^+e^- \to D^o\bar{D}^o\gamma$	$3r_D + 8y\,tg^2\theta_c\lvert\hat{\rho}_{K\pi}\rvert + 4tg^4\theta_c\lvert\hat{\rho}_{K\pi}\rvert^2$	$4tg^4\theta_c\lvert\hat{\rho}_{K\pi}\rvert^2$
iii. $e^+e^- \to D^o\bar{D}^o\pi^o$	r_D	0 !

Table 2

We draw the following conclusions from Table 1 and 2:

- Comparing the three reactions (i), (ii), and (iii) provides an unambiguous signature for $D^0\bar{D}^0$ mixing as the source of the unusual events.
- It allows us valuable cross checks on systematic uncertainties.
- One can extract $x = \frac{\Delta m}{\Gamma}$ and $y = \frac{\Delta\Gamma}{2\Gamma}$ separately in the non-leptonic decays

(remember $r_D \approx (x^2+y^2)/2$ and keep in mind that $|\hat{\rho}_{K\pi}|$ can be extracted from the data on $BR(D^0 \to K^+\pi^-)$).

Table 2 states that no like-sign di-kaons can be produced in $e^+e^- \to D^0\bar{D}^0\ (\pi^0)$ in the absence of mixing. This observation can actually be generalized: let f_a and f_b denote final states of strangeness $S = +1$ and let $\bar{f}_a$ and $\bar{f}_b$ be their anti-states which therefore carry $S = -1$; ignore $D^0\bar{D}^0$ mixing, i.e., $x = 0 = y$. Comparing the reaction rates for

$$e^+e^- \to 1\gamma \to D^0\bar{D}^0 \to f_a f_b\,,\ \bar{f}_a\bar{f}_b\,,\ \text{i.e. } S = \pm 2 \tag{13}$$

with

$$e^+e^- \to 1\gamma \to D^0\bar{D}^0 \to f_a\bar{f}_b\,,\ \bar{f}_a f_b\,,\ \text{i.e. } S = 0 \tag{14}$$

one finds [3]

$$\frac{N\left(f_a f_b + \bar{f}_a\bar{f}_b\right)}{N\left(f_a\bar{f}_b + \bar{f}_a f_b\right)} = tg^4\theta_c \left|\hat{\rho}_{f_a} - \hat{\rho}_{f_b}\right|^2 \tag{15}$$

where I have assumed CP invariance again:

$$tg^2\theta_c\hat{\rho}_f = \frac{T\left(D^0 \to f\right)}{T\left(D^0 \to \bar{f}\right)} = \frac{T\left(\bar{D}^0 \to \bar{f}\right)}{T\left(\bar{D}^0 \to f\right)} \tag{16}$$

The origin of the minus sign in $\hat{\rho}_{f_a} - \hat{\rho}_{f_b}$ is easily understood: the initial $D^0\bar{D}^0$ pair forms an odd eigenstate of C and is thus represented by

$$|\, D^0\bar{D}^0 >_{C=-} = \frac{1}{\sqrt{2}}\left(|\ D^0\,(p_L)\,\bar{D}^0\,(p_R) > - |\ D^0\,(p_R)\,\bar{D}^0\,(p_L) >\right) \tag{17}$$

where p_L and p_R denote momenta. As long as f_a and f_b can come from a D^0 as well as a $\bar{D}^0$ meson, i.e., $\hat{\rho}_{f_a} \cdot \hat{\rho}_{f_b} \neq 0$ one has to add the two contributions coherently and – because of (17) – this has to happen with a negative sign.

For $f_a = f_b$ one obviously has $\hat{\rho}_{f_a} = \hat{\rho}_{f_b}$ and (15) yields a vanishing ratio, as exemplified in Table 2. This is immediately obvious: for Bose symmetry requires the final state to be *symmetric* under the exchange of $f_a(p_L)$ and $f_a(p_R)$ which is however impossible since they are in a C *odd* configuration (see Eq. (17)).

This simple argument should not be overemphasized, though. For even with $f_a \neq f_b$ one can quite possibly have $\hat{\rho}_{f_a} = \hat{\rho}_{f_b}$. An example of topical interest is provided by

$$\begin{tikzcd}[column sep=small] e^+e^- \arrow[r] & D^oD̄^o \arrow[r] & \left(K^-\rho_1^+\right)_D \arrow[d, start anchor=south, ""] & \left(K^-\rho_2^+\right)_D \arrow[d] \\ & & (\pi^+\pi^o)_1 & (\pi^+\pi^o)_2 \end{tikzcd} \tag{18}$$

The ρ represents a rather wide resonance; so what happens if the invariant masses of the two $(\pi^+\pi^o)$ systems are different, say:

$$\sqrt{s}\,\Big|_{(\pi^+\pi^o)_1} = m_\rho - \Delta \tag{19}$$

$$\sqrt{s}\,\Big|_{(\pi^+\pi^o)_2} = m_\rho + \Delta \tag{20}$$

Bose symmetry then cannot be envoked directly; yet two things have to be kept in mind here:

(a) "Natura non facit saltus" – i.e., we know that the process (18) cannot occur for $\Delta = 0$. This zero in the rate has to be approached in a continuous fashion as $\Delta \to 0$. Thus the overall rate will be reduced signficantly. A double Dalitz plot analysis for the two $K^-\pi^+\pi^o$ final states would have to exhibit this effect.

(b) For reaction (18) we have

$$\hat{\rho}_1 \, tg^2\theta_c = \frac{T\left(\bar{D}^o \to K^-\rho_1^+\right)}{T\left(\bar{D}^o \to K^+\rho_1^-\right)} \tag{21}$$

$$\hat{\rho}_2 \, tg^2\theta_c = \frac{T\left(\bar{D}^o \to K^-\rho_2^+\right)}{T\left(\bar{D}^o \to K^+\rho_2^-\right)}$$

i.e., the $(\pi^+\pi^o)$ and the $(\pi^-\pi^o)$ system that are compared have to be taken at the same invariant mass. Unless there is an additional rapid phase variation we still have

$$\hat{\rho}_1 = \hat{\rho}_2 \tag{22}$$

All these arguments cannot be applied for D decays into two vector states

$$D \to VV \tag{23}$$

For such a decay mode – in contrast to D → PP, PV – is described by more than one independent amplitude. Therefore, the reaction

$$e^+e^- \to D^o\overline{D}^o \to (K^*\rho)_D\,(K^*\rho)_D \tag{24}$$

can occur even in the absence of mixing with the only constraint that the two decays are described by different combinations of decay amplitudes. Its analysis could actually yield some interesting information on final state interactions in these decay modes.

B. Theoretical Expectations

(1) *Standard Model*

One concludes on very general grounds that $D^o - \overline{D}^o$ mixing is small, in particular compared to $K^o - \overline{K}^o$ mixing. The real question then is: is $D^o - \overline{D}^o$ mixing small or is it quite tiny?

It seems natural at first sight to employ quark box diagrams (there are 12 of them) to estimate Δm_D. One finds a wide variation in the results – yet one thing remains the same: the resulting numbers for $\Delta\Gamma_D/\Gamma_D$ or m_D/Γ_D are so minute as to render them academic. It is not hard to see why this should be so: due to the GIM mechanism Δm_D has to vanish in the limit of $SU(3)_{FL}$ symmetry; yet $SU(3)_{FL}$ breaking enters via the quark masses – $m_s^2 - m_d^2$ – and is calibrated by M_W^2 thus making it a really tiny effect.

There are two major flaws in this treatment:

(i) We know experimentally that D decays exhibit large $SU(3)_{FL}$ breaking effects; in particular [2]

$$\frac{\Gamma(D^o \to K^+K^-)}{\Gamma(D^o \to \pi^+\pi^-)} \sim 3 \tag{25}$$

(ii) The quark box diagram was treated as if it represented a short distance operator as it is the case for $K^o - \overline{K}^o$. However this does not make much sense here since the internal quarks (in a two-family ansatz) are lighter than the charm quark: $m_d < m_s < m_c$. Thus they can propagate and we are dealing with a non-local operator -- which of course we do not know how to treat. An estimate of Δm_D based on the simple quark box diagram is thus of dubious (if any) meaning.

It is therefore in all likelihood that long distance contributions will dominate $D^o - \overline{D}^o$ mixing. To obtain a rough guestimate of its expected strength one considers the transitions

$$D^o \to PP \to \overline{D}^o$$

where the intermediate pseudoscalar P=K or π can be on- or off-shell. One writes down formally

$$T(D^o \to PP \to \overline{D}^o) = \sin^2\theta_c\{[K\overline{K}] + [\pi\pi] - [K\pi] - [\overline{K}\pi]\} \qquad (26)$$

Using the measured branching ratios $D \to K^+K^-, \pi^+\pi^-$ as input and supplementing them by theoretical guesses, one arrives at the following statements:

- r_D could be as "large" as 10^{-3} in the Standard Model, although $\sim 10^{-4}$ appears as a more reasonable estimate [4].
- Δm_D and $\Delta\Gamma_D$ appear as of roughly comparable size.

These crude guestimates can and will be refined in the future, presumably via a dual track approach:

- further experimental input would be of great help, namely measurements of $BR(D^o \to \pi^o\pi^o)$, $BR(D^o \to K^o\overline{K}^o)$, $BR(D^o \to K^+\pi^-)$, and $BR(D^o \to K^- K^*, \pi\rho)$.
- theoretical progress will be achieved by employing dispersion relations and relying on measured $\pi\pi$, $K\overline{K}$ etc. phase shifts.

That way we will presumably be able to establish that indeed

$$r_D \sim 10^{-5} - 10^{-4} \qquad (27)$$

is expected in the Standard Model.

(2) New Physics

It was already stated that it is expected on very general grounds that $D^o - \overline{D}^o$ mixing is small. That it should be as tiny as indicated in (27) is however due to protection measures against flavour changing neutral currents that are *very specific to the Standard Model.*

As soon as one allows for New Physics – be it an extended Higgs sector with flavour changing neutral currents or be it a non-minimal realization of Supersymmetry [7] – one finds as quite conceivable scenarios:

- $r_D \leq 10^{-2}$ (28)
- $\Delta\Gamma << \Delta m$ (29)

To conclude this chapter on D^0 - $\overline{D}^0$ mixing, let me give a brief "consumer guide":

	r_D	Theoret. odds	Comments
next 5 years	10^{-3} - $5 * 10^{-3}$	conceivable with New Physics	within reach
beyond next 5 years	10^{-4} - 10^{-3}	possible (?) with Standard Model -- likely with New Physics	mandatory
	10^{-5} - 10^{-4}	likely with Standard Model	very desirable

III. CP Violation in D Decays

A. Overview

Imagine Nature giving a course on electroweak forces to two students, one with a very imaginative mind -- the "theorist" -- and the other one with more down-to-earth tendencies -- the "experimentalist". Let us imagine further that Nature would hand out a homework assignment, namely to design a hadron well suited for probing CP symmetry. You can guess what would happen: the first, the more frivolous student would come up with beauty hadrons; their decays can exhibit CP asymmetries with slow and with rapid oscillations, direct CP violations, etc.etc. probing the whole width and depth of the KM matrix.

The second, more serious student would come up with the charm system. For he or she could point out that D decays are well suited for actually performing empirical studies of CP invariance. First I will list these reasons before explaining them in somewhat more detail:

- Charm production rates are already sizeable at rather low energies.
- The effective branching ratios, i.e., branching ratios into pions and kaons, are rather decent for relevant modes; for example, we have for decays into self-conjugate modes [2]

$$BR(D^0 \rightarrow \pi^+\pi^-) \approx 0.2\ \% \qquad (30)$$

$$\mathrm{BR}(D^o \to K^+K^-) \approx 0.5\ \% \tag{31}$$

$$\mathrm{BR}(D^o \to K_S K^+K^-) \approx 0.6\ \% \tag{32}$$

- D^* decays provide "user friendly" flavour tagging

$$D^{*+} \to D^o\pi^+ \ \text{vs}\ \ D^{*-} \to \overline{D}^o\pi^- \tag{33}$$

- "What used to be vices, have become virtues" -- great environmental benefits can be reapt from the fact that D decays are affected by final state interactions (= FSI).
- Lastly, but maybe not least, for the empirical researcher: the only experimental bound that exists at present for CP violation in D decays is 100%!

This is not the way in which CP violation in charm decays is usually referred to: honesty compels me to add that there are some drawbacks as well; I will return to them later on.

B. Phenomenology

(1) *Fundamentals*

We already know that D^o - $\overline{D}^o$ mixing produces at best a small number of like-sign dileptons in the semi-leptonic decays of D^o - $\overline{D}^o$ pairs, see Table 1 and (8). It is therefore academic to search for a CP asymmetry in these dilepton events.

Nonleptonic D decays are quite another matter, though. I will describe three generic types of CP asymmetries, two of which can be illustrated by the same decay mode:

$$D^o \to P^+P^- \tag{34}$$

where P^+P^- denotes $\pi^+\pi^-$ or K^+K^-. For the CP conjugate reactions one obtains the following general expressions:

$$\text{rate}\ (D^o(t) \to P^+P^-) = e^{-\Gamma t}|T_{pp}|^2\,(1 - \sin \Delta m t\, A_{PP}) \tag{35}$$

$$\text{rate}\ (\overline{D}^o(t) \to P^+P^-) = e^{-\Gamma t}|\overline{T}_{pp}|^2\,(1 + \sin \Delta m t\, A_{PP}) \tag{36}$$

(a) Direct CP Violation

If the two "reduced", i.e., time-independent partial widths differ

$$|T_{pp}|^2 \neq |\overline{T}_{pp}|^2 \tag{37}$$

then there is CP violation in purely ΔCharm = 1 transitions. There are two necessary conditions for (37) to be realized:

- Two independent amplitudes have to contribute to the same final state. Within the Standard Model (and without mixing) only Cabibbo suppressed modes can satisfy this criterion.
- Unless FSI provide non-trivial strong phase shifts between the two amplitude, no CP asymmetry could be observed even if CP violating weak phases were present.

The need for the intervention of such FSI makes it obviously hard to arrive even at rough estimates in predicting possible CP asymmetries. On the other hand, since D decays proceed in a dynamical environment full of resonances, it would be quite surprising if the appropriate FSI were not present in at least some of the decay channels. In the overview, I had referred to this situation as a great environmental benefit of D decays. Analogous considerations apply in charged charm decays, i.e., D^+, D_s^+ and Λ_c^+ decays.

(b) CP Violation Involving D^o - $\overline{D}^o$ mixing

Another type of CP asymmetry is described by the quantity A_{PP}; it can however be observed only if D^o - $\overline{D}^o$ mixing occurs, i.e., if $\Delta m \neq 0$. Yet it should be kept in mind that for $y << x << 1$ the following simple relation holds

$$\sin \Delta mt \cong \frac{\Delta m}{\Gamma}\frac{t}{\tau_D} \cong \sqrt{2}\, r_D \frac{t}{\tau_D} \tag{38}$$

Thus

$$\text{rate}\ (D^o(t) \rightarrow P^+P^-) \cong e^{-\Gamma t}\, \hat{T}_{PP}\left(1 - \sqrt{2}\, r_D \frac{t}{\tau_D} A_{PP}\right) \tag{39}$$

Therefore even with a small r_D, say

$$r_D \sim 3 \times 10^{-3}$$

a CP asymmetry of ~4% is quite conceivable at $t \cong 2\ \tau_D$ if A_{PP} could be as large as 0.25. (As discussed later such a value for A_{PP} requires the intervention of New Physics.)

(c) CP Asymmetries in Final State Distributions

I had already mentioned in Sect. II that the decay

$$D \rightarrow VV$$

is described by more than one independent amplitude. Thus the dynamical information inherent in such decays goes beyond the mere decay rate; it is contained also in non-trivial correlations in the final state. Consider for example [5]

$$D^+ \rightarrow \overline{K}^{o*}K^{+*} \tag{40}$$

and let $\vec{\varepsilon}_+$, $\vec{\varepsilon}_o$ and $\vec{p}_o$ denote the polarization of K^{+*}, $\overline{K}^{o*}$ and the momentum of the latter, respectively. One can then study the triple correlation

$$N_+ = \left\langle \vec{p}_o \cdot \left(\vec{\varepsilon}_o \,\mathrm{x}\, \vec{\varepsilon}_+ \right) \right\rangle \qquad (41)$$

i.e., the expectation value for the component of the $\overline{K}^{o*}$ momentum that is perpendicular to the plane spanned by $\vec{\varepsilon}_o$ and $\vec{\varepsilon}_+$..

Since under time reversal T

$$\begin{array}{c} \vec{p} \rightarrow -\vec{p} \\ T \\ \vec{\varepsilon} \rightarrow -\vec{\varepsilon} \end{array} \qquad (42)$$

one realizes immediately that the correlation N_+ is T odd. A non-vanishing value for N_+ does, however, not establish a violation of T or CP invariance. Since T is described by an <u>anti</u>-unitary operator,

$$N_+ \neq 0$$

can be due to CP violation or to FSI (or both). To perform a stringent test of CP invariance one has to study also the CP conjugate reaction,

$$D^- \rightarrow K^{o*} K^{-*} \qquad (43)$$

determine

$$N_- \equiv \left\langle \vec{p}_o \cdot \left(\vec{\varepsilon}_o \,\mathrm{x}\, \vec{\varepsilon}_- \right) \right\rangle \qquad (44)$$

and compare it with N_+. CP invariance requires

$$N_+ + N_- = 0 \qquad (45)$$

to hold even when FSI produce $N_+ \neq 0 \neq N_-$. CP symmetry is thus violated if

$$N_+ + N_- \neq 0 \qquad (46)$$

were observed.

(2) Search Scenarios

(a) Direct CP Violation

Asymmetries due to direct CP violation – may they affect partial rates, see (37), or CP conjugate distributions, see (41, 44, 46) – do not depend on the time evolution of the decay rate. The reaction

$$e^+e^- \rightarrow \psi'' \rightarrow D\overline{D}$$

is therefore perfectly suitable for searching for such phenomena.

(b) CP violation involving D^o - $\bar{D}^o$ mixing

The situation changes however dramatically when mixing is involved in a CP asymmetry (see (35, 36)). The defining property of the final states that can be employed here is that they are *shared* by both D^o and $\bar{D}^o$ decays (they also happen to be CP eigenstates though that is not crucial); as such they cannot reveal whether they originated in a D^o or a $\bar{D}^o$ decay and one cannot even define a CP asymmetry. To overcome this obstacle one has to obtain independent information on the flavour of the decaying meson. This "flavour tagging" can be achieved by observing a flavour specific decay of the other neutral D meson; semileptonic decays and those involving a single charged K are suitable modes:

$$\begin{array}{l} e^+e^- \rightarrow D^o\bar{D}^o + \ldots \\ \qquad\quad \lfloor\!\longrightarrow \ell^- X \\ \qquad\; \lfloor\!\longrightarrow P^+P^- \end{array} \qquad \text{vs.} \qquad \begin{array}{l} e^+e^- \rightarrow D^o\bar{D}^o + \ldots \\ \qquad\quad \lfloor\!\longrightarrow P^+P^- \\ \qquad\; \lfloor\!\longrightarrow \ell^+ X \end{array} \tag{47}$$

With a CP asymmetry thus defined one can analyze the same three production processes for D^o - $\bar{D}^o$ pairs as listed in Table 1. Integrating over all times of decay for the D^o and the $\bar{D}^o$ one obtains the results shown in Table 3 [3]:

	reaction	$< \text{CP Asym} >_{time}$	$C[D^o\bar{D}^o]$
i.	$e^+e^- \rightarrow D^o\bar{D}^o$	0 ! (*)	-
ii.	$e^+e^- \rightarrow D^o\bar{D}^{*o}$ + h.c. $\rightarrow D^o\bar{D}^o\gamma$	$2\sqrt{2}\, r_D\, A_{pp}$	+
iii.	$e^+e^- \rightarrow D^o\bar{D}^{*o}$ + h.c. $\rightarrow D^o\bar{D}^o\pi^o$	0 ! (*)	-

Table 3

(*) (i.e., direct CP violation only)

The quantity $< \text{CP Asym} >_{time}$ is here defined as the CP asymmetry in the combined decay probability

$$\frac{N[(\ell^- X)_D\, (P^+P^-)_{\bar{D}}] - N[(\ell^+ X)_{\bar{D}}\, (P^+P^-)_D]}{N[(\ell^- X)_D\, (P^+P^-)_{\bar{D}}] + N[(\ell^+ X)_{\bar{D}}\, (P^+P^-)_D]}$$

integrated over all t and $\bar{t}$, i.e. the times of decay for D^o and $\bar{D}^o$ mesons respectively.

The origin of the difference in the CP asymmetry for reaction (i) and (iii) on one side and (ii) on the other is easily found. For the time dependence of the asymmetry is given by

$$\text{CP asym }(t, \bar{t}) \;\propto\; \left\{ \begin{array}{lcl} e^{-\Gamma(t+\bar{t})}\sin\left(\Delta m\,(t-\bar{t})\right) & & \text{odd} \\ & \text{for } C = & \\ e^{-\Gamma(t+\bar{t})}\sin\left(\Delta m\,(t+\bar{t})\right) & & \text{even} \end{array} \right. \qquad (48)$$

Integrating (48) *symmetrically* over t and $\bar{t}$ yields the results stated in Table 3. From it we draw the following conclusions:

- Comparing possible CP asymmetries that can emerge in the three reference reactions (i) - (iii) provides an unambiguous signal for a CP violation that involves D^0 - $\bar{D}^0$ mixing.
- This provides us with valuable cross checks on systematic uncertainties – as it was the case with D^0 - $\bar{D}^0$ mixing.
- An asymmetry appearing in reaction (i) is therefore either due to direct CP violation or to detector bias.

(c) CP violation producing a rate, not an asymmetry

Let us consider the reaction

$$e^+e^- \to \psi'' \to D^0\bar{D}^0 \to f_a f_b \qquad (49)$$

where f_a and f_b represent CP eigenstates of the same CP parity, i.e.

$$\begin{aligned} CP\,|f_a\rangle &= \eta_a\,|f_a\rangle \\ CP\,|f_b\rangle &= \eta_b\,|f_b\rangle \\ \eta_a\eta_b &= +1 \end{aligned} \qquad (50)$$

The process (49) can proceed only in the presence of CP violation: for

$$CP\,|\psi''\rangle = +\,|\psi''\rangle$$

whereas

$$CP\,|f_a f_b\rangle = \eta_a\eta_b(-1)^{l=1}\;|f_a f_b\rangle = -\,|f_a f_b\rangle \qquad (51)$$

Thus

$$\text{CP (initial)} \neq \text{CP (final)} \qquad (52)$$

and CP invariance is broken.

By explicit calculation one obtains

$$BR\left(D^o\overline{D}^o|_{C=-} \rightarrow f_a f_b\right) \cong BR(D \rightarrow f_a)\, BR(D \rightarrow f_b)$$

$$\left\{2\left|\overline{\rho}\,(f_a) - \overline{\rho}\,(f_b)\right|^2 + 2r_D\left|1 - \overline{\rho}\,(f_a)\,\overline{\rho}\,(f_b)\right|^2\right\} \tag{53}$$

$$\overline{\rho}\,(f) \equiv \frac{T(\overline{D}^o \rightarrow f)}{T(D^o \rightarrow f)}$$

The first term in the curly bracket represents direct CP violation, the second one CP violation involving D^o - $\overline{D}^o$ mixing (it vanishes for $r_D \rightarrow 0$).

Not surprisingly, both terms add to the rate. Thus, by ignoring the second term, we decrease the signal – most dramatically of course for $f_a = f_b$, i.e., identical final states. To illustrate the power of (53), I will set $r_D = 0$ and use the definition

$$\overline{\rho}(f_i) = \left|\overline{\rho}(f_i)\right| e^{i\,\alpha_i} \tag{54}$$

$\left|\overline{\rho}(f_i)\right| \neq 1$ represents direct CP violation that would show up already as a difference between the single particle decay rates (35) and (36).

$$BR(D^o\overline{D}^o|_{C=-} \rightarrow f_a f_b) \cong 2BR(D \rightarrow f_a)\, BR(D \rightarrow f_b) \bullet$$

$$\bullet \left|\,\overline{\rho}\,(f_a)\right|^2 \left|\,1 - \left|\frac{\overline{\rho}\,(f_b)}{\overline{\rho}\,(f_a)}\right| e^{i\,(\alpha_b - \alpha_a)}\right|^2 \tag{55}$$

Let us make some simplifying assumptions to illustrate the content of Eq. (55):

$$\left|\overline{\rho}\,(f_a)\right| = 1 \tag{56a}$$

$$\left|\overline{\rho}\,(f_b)\right| = 1 - \frac{1}{2}\Delta_b,\ \Delta_b\ << 1 \tag{56b}$$

$$\alpha_b - \alpha_a = \delta\alpha << 1 \tag{56c}$$

In this scenario one obtains

$$BR\left(D^o\overline{D}^o|_{C=-} \rightarrow f_a f_b\right) \cong BR\left(D \rightarrow f_a\right) BR\left(D \rightarrow f_b\right)\left(\frac{1}{2}\Delta_b^2 + 2\,(\delta\alpha)^2\right) \tag{57}$$

Two comments are in order here:

(i) Eqn. (56b) implies

$$\left|\overline{\rho}\,(f_b)\right|^2 \cong 1 - \Delta \tag{58}$$

Not surprisingly, the decay rate asymmetry (58) -- which is the same as the one in (37) -- is *linear in Δ* whereas the CP violating process (57) is *quadratic in it.*

(ii) CP violating due to a phase $\delta\alpha \neq 0$ could *not* be observed via an asymmetry between CP conjugate decay rates as listed in (37) since such phases drop out from single particle decay rates. Only the *interference* between the two decays $D \rightarrow f_a$ and

$D \to f_b$ is sensitive to the presence of $\delta\alpha$. (It should be noted here that CP violation involving D^o-$\overline{D}^o$ mixing, see Table 3, also depends on these phases α_a and α_b relative to that generated by D^o-$\overline{D}^o$ mixing.)

Some examples will help to illustrate the relative merits of the different methods to search for CP violation:

(i) The decay modes

$$D \to K^+K^-, \pi^+\pi^-$$

command branching ratios of ~ 5×10^{-3} and ~ 2×10^{-3} respectively. To look for a 1% asymmetry, i.e. $\Delta = 0.01$, in flavour tagged events

$$e^+e^- \to D^o\overline{D}^o \to (\ell^+/K^-X)_D (P^+P^-)_D \text{ vs. } (\ell^-/K^+X)_D (P^+P^-)_D \tag{59}$$

$$P^+P^- = K^+K^-, \pi^+\pi^-$$

then requires ~ 10^7 D^oD^o pairs if the tagging efficiency, acceptance etc. amount to 10 %.

(ii) To see a single event

$$e^+e^- \to D^o\overline{D}^o \to (K^+K^-)_D (\pi^+\pi^-)_D \tag{60}$$

then requires ~ 10^9 $D^o\overline{D}^o$ pairs if $\Delta = 0.01$, $\delta\alpha = 0$. If on the other hand $\delta\alpha = 0.1$ were to hold then a sample of~ 10^7 $D^o\overline{D}^o$ would produce two events (for perfect detection efficiency). As already stated, effects due to $\delta\alpha \neq 0$ could show up only in reaction (60), not in the decay rate comparison (59).

(iii) A subtle, yet important effect has to be noted in

$$e^+e^- \to D^o\overline{D}^o \to (K_L\pi^o)_D (K^+K^-)_D \tag{61}$$

namely the *known CP violation in the* K^o - $\overline{K}^o$ *complex*. For K_L contains a small admixture of a CP even component in its wave function: $K_L^{(CP+)}$; $K_L^{(CP+)}\pi^o$ is then an odd CP eigenstate thus making reaction (61) proceed even in the absence of CP violation in ΔCharm = 1 processes, i.e., D decays. One actually finds in that case

$$\begin{aligned} &BR(D^o\overline{D}^o|_{C=-} (K_L\pi^o)_D (K^+K^-)_D) \cong \\ &\qquad [2BR(D \to K_L\pi^o)BR(D \to K^+K^-)] \bullet 4\, BR(K_L \to \pi^+\pi^-) \\ &\qquad \cong 8 \times 10^{-7} \end{aligned} \tag{62}$$

Any deviation from this number if observed – be there more events or fewer events – establishes *CP violation in D decays* (once the branching ratios $BR(D \to \overline{K}^o\pi^o, K^+K^-)$ are sufficiently well measured).

(iv) As is quite apparent from Eqn. (55) there is interference between CP violation in $D \to f_a$ and $D \to f_b$. Again reaction (61) can profitably be used to illustrate this point:

$$\begin{gathered} \bar{\rho}\,(K^+K^-) \cong 1 - \frac{1}{2}\,\Delta_{KK} - i\,\alpha_{KK} \\ \bar{\rho}\,(K_L\pi^o) \cong \frac{1-\varepsilon}{1+\varepsilon} \end{gathered} \tag{63}$$

(within the KM ansatz the Cabibbo *allowed* mode $D \to K_L\pi^o$ cannot exhibit direct CP violation in ΔCharm = 1 transitions.) We then find

$$\begin{gathered} BR(D^o\bar{D}^o|_{C=-}\ (K_L\pi^o)_D\,(K^+K^-)_D) \cong \\ [2BR(D \to K_L\pi^o)BR(D \to K^+K^-)] \\ \left[(4BR(K_L \to \pi^+\pi^-) + \left(\alpha_{KK}^2 + \frac{1}{4}\,\Delta_{KK}^2\right) + 2\sqrt{2BR(K_L \to \pi^+\pi^-)}\left(\alpha_{KK} + \frac{1}{2}\,\Delta_{KK}\right)\right] \end{gathered} \tag{64}$$

using a phase of 45^o for ε; the third term in the curly brackets denotes the interference between $T(D \to K_L^{(CP+)}\pi^o)$ and $T(D \to K^+K^-)$. For

$$\begin{gathered} \Delta_{KK} = 0.01 \\ \alpha_{KK} = 0.02 \end{gathered} \tag{65}$$

we obtain

$$BR(D^o\bar{D}^o|_{C=-}\ (K_L\pi^o)_D\,(K^+K^-)_D) \cong 1.2 \times 10^{-6} \tag{66}$$

i.e., a *50% increase* over (62) where $D \to K^+K^-$ was assumed to be CP conserving: $\Delta_{KK} = 0 = \alpha_{KK}$. This sizeable increase is driven mainly by the interference.

(v) There are actually quite a few D decay modes that can profitably be employed here:

$$D^o\bar{D}^o|_{C=-} \to (K_L\pi^o/K_L\eta/K_L\eta')_D + (K^+K^-/K_sK_s/\pi^o\pi^o)_D \tag{67}$$

$$D^o\bar{D}^o|_{C=-} \to (K^+K^-)_D + (\pi^+\pi^-/K_SK_S/\pi^o\pi^o)_D \tag{68a}$$

$$\to (\pi^+\pi^-)_D + (K_sK_s/\pi^o\pi^o)_D \tag{68b}$$

$$\to (K_sK_s)_D + (\pi^o\pi^o)_D \tag{68c}$$

Identical pairs like $(K^+K^-)_D + (K^+K^-)_D$ have been left out since they cannot occur in the absence of $D^o\bar{D}^o$ mixing, i.e, for $r_D = 0$ which is our working hypothesis for the moment.

It would be tempting to include $D \to K_L\omega$, $K_L\rho^o$ etc. The sizeable widths of these resonances – ω, ρ^o, etc. – makes it however very difficult to differentiate between the final state $K_L\rho^o$, which is a CP eigenstate, and $K^{-*}\pi^+$ which is not etc. A Dalitz plot analysis of the $K_L\pi^+\pi^-$ final states would in principle allow to disentangle these complexities yet it appears that even 10^7 $D^o\bar{D}^o$ pairs would not allow such a detailed analysis.

Reactions (68a, b, c) are sensitive to direct CP violation in these Cabibbo disfavored D^o decays. Reactions (67) on the other hand are sensitive to the interplay of these CP violations with that in K^o - $\overline{K}^o$ mixing. With

$$BR(D \to K_L\pi^o) \cong BR(D \to K_L\eta) \cong BR(D \to K_L\eta') \cong 1\%$$

$$BR(D \to K^+K^-) \cong 0.5\%$$

$$BR(D \to K_SK_S) \cong 0.1\%$$

$$BR(D \to \pi^+\pi^-) \cong BR(D \to \pi^o\pi^o) \cong 0.2\%$$

one infers

$$BR(D^o\overline{D}^o|_{C=-} \to \left((K_L\pi^o/K_L\eta^{(\prime)})_D + (K\overline{K}/\pi\pi)\right) \cong 5 \text{ x } 10^{-6} \tag{69}$$

under the assumption that $K_L \to \pi\pi$ is the only CP violation present. The scenario of Eq. (63) - (66) can be extended to the sum of these decay modes:

$$BR(D^o\overline{D}^o|_{C=-} \to \left((K_L\pi^o/K_L\eta^{(\prime)})_D + (K\overline{K}/\pi\pi)\right) \cong 7 \text{ x } 10^{-6} \tag{70}$$

A sample of 10^7 or few x 10^7 $D^o\overline{D}^o$ pairs produced on the ψ'' resonance might allow us to probe the difference between (69) and (70) which represents CP asymmetries in neutral D decays on the one percent level!

Considering the low relative probability for these events to occur one might raise the following concern: the argument that the CP parity of the initial state is even was based on the assumption that the D^o-$\overline{D}^o$ pair was produced by the ψ'' resonance or -- more generally -- by a one-photon intermediate state, see (49)-(52). What about bremsstrahlung of photons which are of order α relative to the process (49)? Bremsstrahlung off the electrons or positrons does not change the fact that the D^o-$\overline{D}^o$ pair is produced by a one-photon intermediate state; bremsstrahlung off the *neutral* D mesons is cut off at low energies and soft photons can therefore not cause a problem.

C. Theoretical Guestimates

(1) Standard Model

(a) Overview

As it is with $D^o\overline{D}^o$ mixing one concludes on fairly general grounds that the Standard Model generates only rather small CP asymmetries in D decays. The relevant question is then again: how small or tiny are they?

CP asymmetries depend crucially on the interference between different transition amplitudes with different KM parameters. Is it then not surprising that theoretical predictions on CP asymmetries in D decays are even more uncertain than those on $D^o\overline{D}^o$ mixing. A look at the KM matrix in the Wolfenstein representation will help to obtain a first point of orientation:

$$V_{KM} = \begin{array}{cc} \begin{matrix} d & s & b \end{matrix} & \\ \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3\left(\rho - i\eta\,(1 - \frac{1}{2}\lambda^2)\right) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 - i\eta A^2\lambda^4 & A\lambda^2\left(1 + i\eta\lambda^2\right) \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} & \begin{matrix} u \\ c \\ t \end{matrix} \end{array} \quad (71)$$

with

$$\lambda \cong \sin\theta_c$$
$$A \cong 1 \pm 0.2$$
$$\rho^2 + \eta^2 \leq 0.4$$

Counting just the KM parameters involved one arrives at the following rough guestimates:

- CP violation in $D^o\overline{D}^o$ mixing which is in analogy to ε_K and which can be measured in $D^o\overline{D}^o \rightarrow \ell^+\ell^+X/K^-K^-X$ vs. $D^o\overline{D}^o \rightarrow \ell^-\ell^-X/K^+K^+X$ is of order $\eta\lambda^5 \sim 10^{-4}$. Discussing such a CP asymmetry is however academic since we already know that $D^o\overline{D}^o$ mixing produces at best very small numbers of like-sign dileptons and dikaons.
- CP asymmetries in non-leptonic D decays are however another and less hopeless affair: they are of order $\eta\lambda^4 \leq 10^{-3}$ and the relevant branching ratios are larger.

The lesson we draw from this is that the Standard Model generates quite small, but not truly minute CP asymmetries in D decays: their natural scale is given by $O(10^{-4})$. As such they would be smaller than CP violation in $\Delta S=2$ mixing – $|\varepsilon_K| \sim 2 \times 10^{-3}$ – yet larger than the direct CP violation in $\Delta S=1$ transitions – $|\varepsilon'| \sim 7 \times 10^{-6}$.

Yet at the same time, we have to be wary of such sweeping statements, in particular when they are based on just adding up and multiplying KM parameters. D decays are known to be affected by significant strong final state interactions (= FSI); those enhance certain transition amplitudes and suppress others. Therefore, they can have a great impact on the size of observable CP asymmetries. Since FSI are quite specific to a certain decay mode, we have to discuss various decays case by case.

(b) Some examples

D decays leading to final states that are CP eigenstates can –as described before – exhibit almost the whole range of observable CP asymmetries. Therefore we turn our attention to

$$D \rightarrow K^+K^-, \pi^+\pi^-, K_SK_S \qquad (72)$$

Those are Cabibbo suppressed transitions; thus more than one transition amplitude contributes – a necessary condition for an observable CP asymmetry.

There are spectator diagrams and Penguin diagrams that produce $D \rightarrow K^+K^-, \pi^+\pi^-$. In addition there are W-exchange diagrams and in particular rescattering is bound to occur on some level producing $D \rightarrow K_SK_S$ and affecting $D \rightarrow K^+K^-, \pi^+\pi^-$ as well. Thus there is no shortage of different transition amplitudes contributing coherently and with different strong phases to the same process. The uncertainties arise when one attempts to obtain quantitative predictions. Experimentally we know that

$$\frac{BR(D \rightarrow K^+K^-)}{BR(D \rightarrow \pi^+\pi^-)} \sim 3 \qquad (73)$$

holds – an apparent large violation of $SU(3)_{FL}$ symmetry. Pure spectator diagrams would yield a ratio of ~1.4. Thus we infer from (73) that other mechanisms like Penguin diagrams and/or rescattering processes contribute signficantly. Unfortunately rescattering and those Penguin diagrams with an *internal* s (or d) quark are controlled by *long-distance dynamics;* therefore their weight cannot be predicted in a reliable fashion. Only Penguin operators with an internal b quark are local operators open to a short-distance treatment; yet their numerical weight is tiny due to the smallness of $|V(cb)V(ub)|$.

The decay

$$D \rightarrow \pi^+\pi^- \qquad [D \rightarrow K^+K^-]$$

receives contributions from three different sources:

(i) The spectator process

$$c \rightarrow u\,\bar{d}\,d \qquad [c \rightarrow u\,\bar{s}\,s]$$

with KM parameters

$$V(cd)\,V^*(ud) \qquad [V(cs)\,V^*(us)] \qquad (74)$$

(ii) The rescattering reaction

$$D \rightarrow "K\bar{K}" \rightarrow \pi^+\pi^- \qquad [D \rightarrow "\pi\pi" \rightarrow K^+K^-]$$

with

$$V(cs)\,V^*(us) \qquad [V(cd)\,V^*(ud)] \qquad (75)$$

(iii) The Penguin process

$$c \rightarrow u + \text{glue}$$

where it is only the strong transition

$$\text{glue} \rightarrow d\bar{d} \qquad [\text{glue} \rightarrow s\bar{s}]$$

that distinguishes between $D \to \pi\pi$ and $D \to K\bar{K}$. Its dependence on the weak quark parameters is given by

$$V(cs)\, V^*(us) \log \frac{M_W^2}{m_s^2} + V(cd)\, V^*(ud) \log \frac{M_W^2}{m_d^2} \qquad (76)$$

As is read off from (71) a weak complex phase can enter via V(cs) only (in this representation of the KM matrix); thus we have to keep track of it. Unfortunately we cannot – as already stated – estimate the relative weight of these different contributions in a reliable fashion. Yet to obtain a rough guestimate one can proceed as follows: to reproduce the observed ratio in (73) one has to invoke a ~25% contribution (in amplitude) from rescattering and/or Penguins that interferes *destructively* in $D \to \pi^+\pi^-$ and *constructively* in $D \to K^+K$. In that case one would guestimate a $\sim 10^{-3}$ difference in $T(D^o \to \pi^+\pi^-)$ vs. $T(\bar{D}^o \to \pi^+\pi^-)$ and a $\sim$ few 10^{-4} difference in $T(D^o \to K^+K^-)$ vs. $T(\bar{D}^o \to K^+K^-)$; to be more specific: with the definitions

$$\bar{\rho}(D \to f) = |\,\bar{\rho}_f|\, e^{i\alpha_f}$$

one finds

$$|1 - \bar{\rho}_f| \sim \left\{ \begin{array}{lcl} 10^{-3} & & \pi^+\pi^- \\ & \text{for } f = & \\ \text{few x } 10^{-4} & & K^+K^- \end{array} \right. \qquad (77)$$

$$\alpha_f \sim \left\{ \begin{array}{lcl} 10^{-3} & & \pi^+\pi^- \\ & \text{for } f = & \\ \text{few x } 10^{-4} & & K^+K^- \end{array} \right. \qquad (78)$$

There could be (and probably are) some other strong interaction effects that influence the size of various hadronic matrix elements and can thus enhance – or suppress – CP asymmetries in non-leptonic D decays. These changes could well amount to a factor of three or so, but very unlikely to an order of magnitude: for such spectacular matrix element enhancements had to show up in rather massive discrepancies between the predicted and the measured branching ratios – something that has not emerged in the data yet. Therefore *within the Standard Model one expects CP asymmetries of at most few x 10^{-3} in the transitions $D \to \pi^+\pi^-$, K^+K^-* [6]. These seem to be just beyond our reach with a sample of 10^7 D's.

CP asymmetries that involve $D^o\bar{D}^o$ mixing as described in (39) are completely beyond reach since $\sqrt{2r_D} \leq 0.04$ in the Standard Model.

(2) New Physics

Models with an extended Higgs sector or non-minimal Supergravity [7] models allow for significantly larger CP asymmetries. There are conceivable scenarios where differences between, say, $T(D^o \to K^+K^-)$ and $T(\bar{D}^o \to K^+K^-)$ or $T(D^o \to \pi^+\pi^-)$ and $T(\bar{D}^o \to \pi^+\pi^-)$ could reach the 10% level (in somewhat extreme cases even more), both in absolute magnitude and in relative phase

$$\left|1 - \rho(D \to P^+P^-)\right| \cong 0.9 \tag{79}$$

$$\alpha_{pp} \cong 0.1 \tag{80}$$

$$P^+P^- = \pi^+\pi^-, K^+K^-$$

$|\rho_{pp}|$ can be measured both on and off the ψ'' resonance; α_{pp} can be searched for in $\psi'' \to D^o\bar{D}^o$ when both D mesons decay into final states that are CP eigenstate of the same CP parity, see (53); or in $e^+e^- \to D^o\bar{D}^{o*}$ + h.c. $\to D^o\bar{D}^o\pi^o$. Since $D^o\bar{D}^o$ mixing is in all likelihood signficantly enhanced in the presence of New Physics the latter case does not represent a purely academic scenario any longer. In particular a value of

$$\frac{\Delta m}{\Gamma}|_D \sim 0.1$$

is possible then. With (80) one finds accordingly (see (39))

$$\begin{aligned} \text{rate}\left(D^o(t) \to P^+P^-\right) &\cong e^{-\Gamma t}\,\hat{T}_{pp}\left(1 - \sqrt{2r_d}\,\frac{t}{\tau_D}\,\alpha_{pp}\right) \\ &\cong e^{-\Gamma t}\,\hat{T}_{pp}\left(1 - 0.01 \text{ x } \frac{t}{\tau_D}\ \right) \end{aligned} \tag{81}$$

i.e., *CP asymmetries on the percent level are quite conceivable.* Furthermore, such CP asymmetries can now emerge also in Cabibbo allowed modes like

$$D \to K_s\pi^o, K_s\eta, K_s\phi$$

etc.

IV. Summary

The quite real possibility to uncover great treasures in charm decays – namely $D^o\bar{D}^o$ mixing and CP violation – beckon us to exploit this window of opportunity in a determined fashion.

Searching for D^o-$\overline{D}^o$ mixing carries a large discovery potential for New Physics since ΔCharm = 2 transitions represents a truly higher order weak process (the only other ones being K^o - $\overline{K}^o$ and B^o - $\overline{B}^o$ mixing).

Discovering CP violation in D decays would be even more spectacular irrespective of whether it is due to New Physics or not. Furhtermore D decays actually carry a structure that is rich enough as to allow experimental distinction between different sources of CP violation.

From these goals one derives bench mark figures for New Initiatives in charm decays:

one has to be able to

- probe $D^o\overline{D}^o$ mixing down to a level of ~ 10^{-4} in r_D, and
- search for CP asymmetries down to the 1% level.

These numbers were chosen because

- they represent improvements over existing data by up to two orders of magnitude and
- New Physics can yield effects of this size
- while the Standard Model is quite unlikely to do so.

Such searches can be performed in many different experimental environments, two of which mark somewhat extreme cases:

A) High energy fixed target experiments where the ability to find visible decay vertices has been shown to be a powerful tool in controlling the background.

B) Low energy e^+e^- annihilation near the charm threshold: one cannot hope here to find visible D decay vertices (except on rare occasions). Yet the fact that in

$$e^+e^- \rightarrow D^o\overline{D}^o, D^o\overline{D}^o\gamma, D^o\overline{D}^o\pi^o$$

we are dealing with *well-defined coherent quantum states* allows us to perform interferometry by exploiting $D\overline{D}$ decay correlations. This will enable us to extract basically the same information that otherwise could be obtained only from the positions of the decay vertices.

The last conclusion we have to keep in mind is the following: there is no space for "experiments on the cheap"; success can come only from <u>dedicated and optimized</u> experimentation.

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[6] For a recent discussion on direct CP violation in D decays, see: M.Golden and B.Grinstein, preprint FERMILAB-PUB-89/48-T, 1989; my perspective is clearly somewhat different from theirs.

[7] I.I.Bigi and A.Masiero, work in preparation.