**CP Violation in D^0-\bar{D}^0 Mixing**

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The existence of D^0-\bar{D}^0 mixing at a detectable level requires new physics, which effectively yields a Δc = 2 superweak interaction. In general this interaction may involve significant CP violation. For small values of the mixing it may be much easier to detect the CP-violating part of the mixing than the CP-conserving part.

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D^0-\bar{D}^0 mixing is expected to be very small in the standard model [1]. While quantitative estimates are difficult because of long-distance effects [2,3], it is clear that x (= Δm_τ/Γ_τ) is well below 10^{-2} whereas the present limit is about 0.06. Future experiments that could probe for a value of x around 10^{-2} would therefore be a way of discovering new physics.

Many extensions of the standard model can lead to D^0, \bar{D}^0 mixing with x \sim 10^{-2}. Examples include models with an extra Q = 2/3 isosinglet quark [4], multi Higgs models with natural flavor conservation [5], and the general two Higgs doublet model (2HDM) with flavor-changing neutral exchange [6]. In these models it is quite natural that there is a significant CP violation associated with the mixing. Here we point out that the study of the time dependence [7] of the decay D^0 \rightarrow K^+\pi^- is particularly sensitive to the CP-violating part of the mixing. Indeed it may be much easier to detect D^0-\bar{D}^0 mixing if it has a sizable CP violation [8] than if it is approximately CP conserving.

The primary effect of the new physics is to produce an effective Δc = 2 superweak interaction. The required strength of such an interaction to yield x ≈ 0.01 is intermediate between that of Δs = 2 and Δb = 2 interactions which would make significant contributions to K^0-\bar{K}^0 and B^0-\bar{B}^0 mixing [9].

In addition to the dependence on Δm, the time evolution of a D^0 beam depends on ΔΓ. We assume here that the new physics does not affect the decays significantly and therefore does not affect ΔΓ. However, in the standard model ΔΓ/Γ is small [2,3] for the same reasons as Δm/Γ; indeed ΔΓ is just the absorptive part of the long-distance diagrams that determine Δm. Thus we neglect ΔΓ.

Including the effects of CP violation, the CP eigenstates D_1(= D^0 + \bar{D}^0) and D_2(= D^0 - \bar{D}^0) are related to the mass eigenstates D_H and D_L by

\[
D_1 = \cosφ D_H + i \sinφ D_L, \\
D_2 = i \sinφ D_H + \cosφ D_L.
\]

The factor i is a consequence of CPT invariance when ΔΓ ≪ Δm, just as in the case [10] of the B^0-\bar{B}^0 system. Then, as a function of time, the state starting as a D^0 evolves with time as

\[
e^{iφ}D^0(τ) = D^0 \cos xτ + e^{2iφ}D^0(-i \sin xτ) = D^0 \cos xτ + e^{iφ}D^0(-i \sin xτ), \tag{2}
\]

where \(τ = tΓ/2\).

The D^0 can decay to K^+\pi^- via the doubly Cabibbo suppressed amplitude (DCSD) \(E A e^{iφ_0}\), where \(E ≈ \tan^2 θ_c ≈ 0.05\). In contrast the allowed decay \(D^0\) has the amplitude \(A e^{iφ_0}\). Here \(δ_A\) and \(δ_D\) are the "strong" phase shifts. It might seem obvious that \(δ_A = δ_D\) since we are dealing with the same final state \(K^+\pi^-\). This would be true if there were only elastic scattering. In fact, the phases \(δ_D\) and \(δ_A\) must be derived from the absorptive part of the amplitudes for \(D^0 \rightarrow K^+\pi^-\) and \(\bar{D}^0 \rightarrow K^-\pi^+\), respectively. These are not the same since the effective weak operators leading to these decays are different. However, one can show that \(δ_A = δ_D\) in the SU(3) limit. By CP invariance, which holds to a very good approximation for the weak decay assumed to be governed by the standard model, the final state phase for \(D^0 \rightarrow K^-\pi^+\) is given by \(δ_A\). By the interchange of the quarks s and d in the effective operators and in the final state, the allowed decay amplitude \(D^0 \rightarrow K^-\pi^+\) becomes the DCSD amplitude \(D^0 \rightarrow K^+\pi^-\), so that in this SU(3) approximation \(δ_A = δ_D\).

With this assumption and letting \(xτ \ll 1\), the decay rate has the time dependence

\[
R(K^+\pi^-) = e^{-2τ} A^2 \frac{2}{2} \left[ 1 + 2\sin(2φ) \frac{xτ}{E} \right] + \left( \frac{x^2 τ^2}{E^2} \right). \tag{3}
\]

For an initial \(\bar{D}^0\) state going to \(K^-\pi^+\) the sign of the \(xτ\) term is reversed. We now see that with these assumptions the linear term in time, which is most sensitive to small values of \(x\), occurs only in the case of CP-violating \(D^0-\bar{D}^0\) mixing. For example, for \(xτ = 0.01\), the CP-violating term is on the order of 40% for \(\sin 2φ = 1\), whereas the quadratic term is only 4%. Of course, the CP violation can be directly detected by comparing the \(D^0\) and \(\bar{D}^0\) decays. If the quadratic term is not detected, one can measure only the product \(x \sin 2φ\), the CP-violating part of the mixing matrix and not \(x\) and \(\sin 2φ\) separately.
For this case it is not necessary to measure the time distribution. The difference between the integrated rate for $D^0 \rightarrow K^+\pi^-$ and that for $\bar{D}^0 \rightarrow K^-\pi^+$ directly measures $x\sin 2\phi$ and reveals both mixing and $CP$ violation. Without our assumptions, of course, this difference could be due to $CP$ violation in some new physics contribution to the decay amplitude. However, whereas there are many models that suggest significant $D^0-\bar{D}^0$ mixing, it is hard to find one that contributes significantly to the decay amplitude.

The general reason that $CP$ violation is important is that $D^0-\bar{D}^0$ mixing depends on $(\Delta m t)$, or $x\tau$, and for small values of $x$ one is most sensitive to the linear term in $x\tau$. This term is odd under the change of $t$ to $-t$. In the absence of "final state interactions," that is, of absorptive parts of diagrams, this corresponds to time reversal. Thus once we set $\Delta \Gamma$ and $\delta_A - \delta_B$ to zero, the term proportional to $x\tau$ must be odd with respect to $CP$.

While we have discussed only the important case of $K\pi$ decay, similar considerations should hold for quasi-two-body final states with the same strangeness content. It is also possible to determine $x\sin 2\phi$ from the $CP$-violating asymmetry [8] between $D^0$ and $\bar{D}^0$ decays to $CP$ eigenstates such as $\pi^+\pi^-$ or $K^+K^-$. This is completely analogous to the proposed experiments in $B^0$ physics [10], except that in the $B^0$ case the mixing is large and has already been determined independently of any $CP$ violation. Of course the asymmetry in this case does not have the $1/E$ enhancement of Eq. (3) and so may be much more difficult to detect.

SU(3) invariance can be badly violated in charm decays so that it is quite possible that $\delta_A - \delta_B$ has a significant value, which allows a linear term in $t$ that is $CP$ conserving. Furthermore, although in general we expect the new physics to produce $CP$ violation in the mixing, in some models the small $CP$ violation in $K^0-\bar{K}^0$ mixing may severely limit the possible values of $x\sin \phi$. Under these circumstances, it may well be the $CP$-conserving linear term in $t$ that will reveal the mixing. The $CP$-violating case has the advantage that it is not necessary to measure the time distribution, while the $CP$-conserving case requires a careful analysis of the $t$ dependence [11]. The main purpose of this note is to point out that under reasonable assumptions it may turn out to be much easier to detect mixing together with $CP$ violation than to detect mixing in other ways.

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[11] In a preprint I received while completing this paper, it is pointed out that for the $CP$-conserving case the deviation from a pure exponential may be difficult to detect when both linear and quadratic terms are present [B. Blaylock, A. Seiden, and Y. Nir, Report No. SCIPP 95/16, WIS 95/16/Apr-PH, 1995, hep-ph/9504306 (to be published)].