hep-ph/9507290, WIS-95/28/Jul-PH

Exploring New Physics with CP Violation in Neutral D and B Decays

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If New Physics contributes significantly to neutral meson mixing, then it is quite likely that it does so in a CP violating manner. In $D^0-\bar{D}^0$ mixing measured through $D^0\rightarrow K^+\pi^-$, CP violation induces a term $\propto te^{-\Gamma t}$ with important implications for experiments. For $B_s-\bar{B}_s$ mixing, a non-vanishing CP asymmetry (above a few percent) $a_{CP}(B_s\rightarrow D_s^+D_s^-)$ is a clear signal of New Physics. Interestingly, this would test precisely the same Standard Model ingredients as the question of whether $\alpha+\beta+\gamma=\pi$.

Talk presented at the
6th International Symposium on Heavy Flavour Physics
Pisa, Italy June 6–10, 1995

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Introduction If New Physics contributes significantly to neutral meson mixing, then it is quite likely that it does so in a CP violating manner. This could have important consequences:

a. In $D^0-\bar{D}^0$ mixing measured through $D^0 \to K^+\pi^-$, a relative phase between the direct decay amplitude and the mixing amplitude induces a term $\propto te^{-\Gamma t}$ with important implications for experiments.
b. In $B^0-\bar{B}^0$ mixing, the theoretical calculation of the mixing suffers from large hadronic uncertainties that makes it difficult to uncover contributions from New Physics. In contrast, in CP asymmetries in neutral B decays into final CP eigenstates, *e.g.* $a_{CP}(B\to\psi K_S)$, the hadronic uncertainties are small and new CP violating contributions to mixing may be clearly signalled.
c. In $B_s-\bar{B}_s$ mixing, the Standard Model CP violating phase in the mixing amplitude is, to a good approximation, equal to that of the $b\to c\bar{c}s$ decay amplitude. Consequently, a non-vanishing CP asymmetry (above a few percent) $a_{CP}(B_s\to D_s^+D_s^-)$ is a clear signal of New Physics. Interestingly, this would test precisely the same Standard Model ingredients as the question of whether $\alpha+\beta+\gamma=\pi$.

In section 2 we study the role of CP violation in $D-\bar{D}$ mixing. The content of this section follows ref. [], but benefits from the very useful discussions with several colleagues, particularly Sandip Pakvasa and Guy Blaylock. In section 3 we prove the relation between $a_{CP}(B_s\to D_s^+D_s^-)$ and the relation $\alpha+\beta+\gamma=\pi$. The content of this section is based on ref. [], but the presentation is different. The investigation of CP asymmetries in B^0 decays as a probe of New Physics has been recently reviewed in ref. [] and is not repeated here.

CP Violation in Neutral D decays The best bounds on $D-\bar{D}$ mixing come from measurements of $D^0\to K^+\pi^-$ []. However, these bounds are still orders of magnitude above the Standard Model prediction for the mixing. If the value of Δm_D is anywhere close to present bounds, it should be dominated by New Physics. Then, new CP violating phases may play an important role in $D-\bar{D}$ mixing. In this section, we investigate the consequences of CP violation from New Physics in neutral D mixing.

There are three types of CP violation in meson decays []: in decay, in mixing and in the interference of mixing and decay. We first argue that only CP violation in the interference of mixing and decay is likely to be relevant in the experimental search for $D-\bar{D}$ mixing through $D^0\to K^+\pi^-$.

(i) *CP Violation in decay*: The decay $D^0\to K^+\pi^-$ proceeds via the quark process $c\to d\bar{s}u$. Within the Standard Model, this is completely dominated by doubly Cabibbo suppressed (DCS) tree amplitudes. There is no reasonable type of New Physics that could contribute to charm decays comparably to the W-mediated diagram. Consequently, $D^0\to K^+\pi^-$ is dominated by the single weak phase $\arg(V_{us}V_{cd}^*)$. Similarly, the Cabibbo-allowed mode, $D^0\to K^-\pi^+$ is dominated by a single weak phase, $\arg(V_{ud}V_{cs}^*)$. It is very safe to assume that there is no CP violation in decay for these modes.

(ii) *CP Violation in mixing*: For the neutral D mass eigenstates to differ from the CP eigenstates, one has to have $\mathrm{Im}(\Gamma_{12}/M_{12}) \neq 0$. If Δm_D is anywhere close to present bounds, then it is clearly dominated by New Physics, $M_{12} \gg M_{12}^{\rm SM}$. On the other hand, there is no reasonable type of New Physics that could enhance Γ_{12} by orders of magnitude, so that very likely $\Gamma_{12} \sim \Gamma_{12}^{\rm SM}$. Therefore, if Δm_D is close to the present bounds, it is very safe to assume that there is no CP violation in mixing. (This assumption may have to be dropped if experiments reach the sensitivity close to the Standard Model estimate.)

(iii) *CP Violation in the interference of mixing and decay*: Within the Standard Model, both the mixing amplitude for neutral D mesons and the decay amplitude for $D \to K\pi$ occur through processes that involve, to a very good approximation, quarks of the first two generations only. Therefore, the relative weak phase between the mixing and decay amplitudes is extremely small. However, most if not all extensions of the Standard Model that allow Δm_D close to the limit involve new CP violating phases. In these models, the relative phase between the mixing amplitude and the decay amplitude is usually unconstrained and would naturally be expected to be of $\mathcal{O}(1)$. (Examples are given below.) CP violation of this type could then be a large effect.

We now investigate the implications of the fact that CP violation in the interference of mixing and decay could be an effect of $\mathcal{O}(1)$ and, moreover, that other types of CP violation are negligibly small. To do that, we first introduce some formalism and notations (see also discussions in [,]).

We define p and q as the strong interaction eigenstate components in the mass eigenstates $D_{1,2}$:

$$D_{1,2} = pD^0 \pm q\bar{D}^0.$$

Denoting the masses and widths of $D_{1,2}$ by $M_{1,2}$ and $\Gamma_{1,2}$, we define their sums and differences:

$$M \equiv \frac{1}{2}(M_1 + M_2), \quad \Delta M \equiv M_2 - M_1,$$
$$\Gamma \equiv \frac{1}{2}(\Gamma_1 + \Gamma_2), \quad \Delta\Gamma \equiv \Gamma_2 - \Gamma_1.$$

We define the four decay amplitudes

$$A \equiv K^+\pi^-|H|D^0, \quad B \equiv K^+\pi^-|H|\bar{D}^0,$$
$$\bar{A} \equiv K^-\pi^+|H|\bar{D}^0, \quad \bar{B} \equiv K^-\pi^+|H|D^0.$$

Finally, we define the phase convention independent quantities

$$\lambda = \frac{p}{q}\frac{A}{B}, \quad \bar{\lambda} = \frac{q}{p}\frac{\bar{A}}{\bar{B}}.$$

Our discussion above of CP violation has the following implications:

(i) As CP violation in decay is negligible,

$$\frac{|A|}{|\bar{A}|} = \frac{|B|}{|\bar{B}|} = 1.$$

(ii) As CP violation in mixing is negligible,

$$\left|\frac{p}{q}\right| = 1.$$

Eqs. and together imply also $|\lambda| = |\bar{\lambda}|$. Furthermore, the following approximations can be safely made:

(iii) We will assume – as confirmed experimentally – that $\Delta M \ll \Gamma$, $\Delta\Gamma \ll \Gamma$ and $|\lambda| \ll 1$.

(iv) We will also take here $\Delta\Gamma \ll \Delta M$, which is very likely if ΔM is close to the bound.

The consequence of $(i) - (iv)$ is the following form for the (time dependent) ratio between the DCS and Cabibbo-allowed decay rates ($D^0(t)$ $[\bar{D}^0(t)]$ is the time-evolved initially pure D^0 $[\bar{D}^0]$ state):

$$\frac{\Gamma[D^0(t) \to K^+\pi^-]}{\Gamma[D^0(t) \to K^-\pi^+]} = |\lambda|^2 + \frac{\Delta M^2}{4} t^2 + \mathrm{Im}(\lambda)\ t,$$
$$\frac{\Gamma[\bar{D}^0(t) \to K^-\pi^+]}{\Gamma[\bar{D}^0(t) \to K^+\pi^-]} = |\lambda|^2 + \frac{\Delta M^2}{4} t^2 + \mathrm{Im}(\bar{\lambda})\ t.$$

This form is valid for time t not much larger than $\frac{1}{\Gamma}$. The time independent term is the DCS decay contribution; the term quadratic in time is the pure mixing contribution; and the term linear in time results from the interference between the DCS decay and the mixing amplitudes. Note that both the const(t) and the t^2 terms are equal in the D^0 and $\bar{D}^0$ decays. However, if CP violation in the interference of mixing and decay is significant, $\mathrm{Im}(\lambda) \neq \mathrm{Im}(\bar{\lambda})$ is possible, and the linear term may be different for D^0 and $\bar{D}^0$.

The experimental strategy should then be as follows [,]: (a) Measure D^0 and $\bar{D}^0$ decays separately. (b) Fit each of the ratios to constant plus linear plus quadratic time dependence. (c) Combine the results for $|\lambda|^2$ and ΔM^2. (d) Compare $\mathrm{Im}(\lambda)$ to $\mathrm{Im}(\bar{\lambda})$.

The comparison of the linear term should be very informative about the interplay between strong and weak phases in these decays. There are four possible results:

1. $\mathrm{Im}(\lambda) = \mathrm{Im}(\bar{\lambda}) = 0$: Both strong phases and weak phases play no role in these processes.
2. $\mathrm{Im}(\lambda) = \mathrm{Im}(\bar{\lambda}) \neq 0$: Weak phases play no role in these processes. There is a different strong phase shift in $D^0 \to K^+\pi^-$ and $D^0 \to K^-\pi^+$.
3. $\mathrm{Im}(\lambda) = -\mathrm{Im}(\bar{\lambda})$: Strong phases play no role in these processes. CP violating phases affect the mixing amplitude.
4. $|\mathrm{Im}(\lambda)| \neq |\mathrm{Im}(\bar{\lambda})|$: Both strong phases and weak phases play a role in these processes.

In all these cases, the magnitude of the strong and the weak phases can be determined from the values of $|\lambda|$, $\mathrm{Im}(\lambda)$ and $\mathrm{Im}(\bar{\lambda})$.

Finding either quadratic or linear time dependence would be a signal for mixing in the neutral D system. However, a non-vanishing linear term does not by itself signal CP violation in mixing, only if it is different in D^0 and $\bar{D}^0$. The linear term could be a problem for experiments: if the phase is such that the interference is destructive, it could partially cancel the quadratic term in the relevant range of time, thus weakening the experimental sensitivity to mixing []. On the other hand, if the mixing amplitude is smaller than the DCS one, the interference term may signal mixing even if the pure mixing contribution is below the experimental sensitivity [,].

Before concluding, we briefly survey some types of New Physics that allow large $D - \bar{D}$ mixing and the source of CP violation in each of them that allows large CP violation in the interference of neutral D mixing and $D \to K\pi$ decay.

Supersymmetry with quark–squark–alignment [] is a unique class of models in that it not only allows but actually requires Δm_D close to the bound. Large Δm_D comes from box diagrams with intermediate gluinos and up and charm squarks. The mixing matrix for gluino–quark–squark couplings has new CP violating phases (not related to the CKM matrix) so that the phase of the mixing amplitude is arbitrary.

Fourth quark generation [] contributes to Δm_D through box diagrams with intermediate b' quarks. The 4×4 charged current mixing matrix has three CP violating phases so that the phase of the mixing amplitude is arbitrary.

Left-handed $SU(2)$-singlet up quarks [] allow the Z-boson to couple non-diagonally to the up sector (and, similarly, right-handed $SU(2)$ doublet up quarks). Large Δm_D may come from Z-mediated tree diagrams. The neutral-current mixing matrix has new CP violating phases (related to new phases in the charged current mixing matrix) so that the phase of the mixing amplitude is arbitrary.

Light scalar leptoquarks [] contribute to Δm_D through box diagrams with intermediate leptons. Scalar leptoquark couplings carry arbitrary new phases so that the phase of the mixing amplitude is arbitrary.

Multi-scalar models with natural flavor conservation [] introduce a charged Higgs that may contribute to Δm_D through box diagrams similar to the SM but with one or two of the W propagators replaced by the charged Higgs. If the diagram with intermediate b quark is large enough, its contribution $\propto V_{ub}^* V_{cb}$ allows the CKM phase to affect $D - \bar{D}$ mixing.

Multi-scalar models without natural flavor conservation [] allow neutral scalars to couple non-diagonally to quarks. A large contribution to Δm_D is possible from scalar mediated tree diagram. The couplings of the scalar may depend on arbitrary new phases, though such phases may give a too large contribution to ϵ_K.

In summary, various extensions of the Standard Model allow large, CP violating, contributions to $D - \bar{D}$ mixing. This will induce an interference term between the DCS contribution and the mixing contribution to $D^0 \to K^+\pi^-$. While such a term may be the consequence of strong phase shifts, a CP violating contribution will be unambiguously signalled if it is different in $D^0 \to K^+\pi^-$ and $\bar{D}^0 \to K^-\pi^+$.

What Does $\alpha + \beta + \gamma = \pi$ Test?

It is often stated that whether the angles α, β and γ measured by the CP asymmetries in *e.g.* $B \to \psi K_S$, $B \to \pi\pi$, and $B_s \to \rho K_S$, respectively, fulfill

$$\alpha + \beta + \gamma = \pi$$

will be a stringent test of the Standard Model. We here wish to show that []

a. If is violated, it will be a clean indication that B_s mixing is *not* dominated by the Standard Model box diagrams, and

b. Precisely the same information will be provided by the much simpler and cleaner test of whether the CP asymmetry in $B_s \to D_s^+ D_s^-$ vanishes,

$$a_{CP}(B_s \to D_s^+ D_s^-) = 0.$$

Let us define the angles α, β, γ and β' in a model independent way:

$$\sin 2\alpha \equiv a_{CP}(B \to \pi^+\pi^-), \quad \sin 2\beta \equiv a_{CP}(B \to \psi K_S),$$
$$\sin 2\gamma \equiv a_{CP}(B_s \to \rho K_S), \quad \sin 2\beta' \equiv -a_{CP}(B_s \to D_s \bar{D}_s).$$

The following two assumptions are practically model independent:

1. The $b \to c\bar{c}s$ and $b \to u\bar{u}d$ processes are dominated by the W-mediated tree diagrams.
2. In the B^0 abd B_s systems $\Gamma_{12} \ll M_{12}$. (This is hardly an assumption as $\Delta M/\Gamma$ is measured to be ~ 0.7 ($\gg 1$) for B^0 (B_s), while modes that contribute to Γ_{12} have branching ratios of order $\lesssim 10^{-3}$ (10^{-1}).)

With these two assumptions, the CP asymmetries in the four modes of eq. always measure the phase between the mixing amplitude and the decay amplitude (though the value of this phase may be different in different models):

$$\alpha = \frac{1}{2}\arg\left[\left(\frac{q}{p}\right)_{B^0}\left(\frac{\bar{A}}{A}\right)_{b\to u\bar{u}d}\right], \quad \beta = \frac{1}{2}\arg\left[\left(\frac{p}{q}\right)_{B^0}\left(\frac{A}{\bar{A}}\right)_{b\to c\bar{c}s}\left(\frac{q}{p}\right)_{K^0}\right],$$
$$\gamma = \frac{1}{2}\arg\left[\left(\frac{p}{q}\right)_{B_s}\left(\frac{A}{\bar{A}}\right)_{b\to u\bar{u}d}\left(\frac{p}{q}\right)_{K^0}\right], \quad \beta' = \frac{1}{2}\arg\left[\left(\frac{p}{q}\right)_{B_s}\left(\frac{A}{\bar{A}}\right)_{b\to c\bar{c}s}\right].$$

(In the derivation of from , one has to take into account that ψK_S and ρK_S are CP-odd.) With the definition of the angles through , each of the equalities in is only defined mod(π).

Within the SM, these angles are interpreted in terms of CKM phases:

$$\alpha^{\rm SM} = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right), \quad \beta^{\rm SM} = \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right),$$
$$\gamma^{\rm SM} = \arg\left(\frac{V_{ub}^* V_{ud} V_{tb}}{V_{cs}^* V_{cd} V_{ts}}\right), \quad \beta'^{\rm SM} = \arg\left(-\frac{V_{cb}^* V_{cs}}{V_{tb}^* V_{ts}}\right).$$

Furthermore, within the Standard Model,

$$\arg\left(\frac{V_{tb}^* V_{ts}}{V_{cb}^* V_{cs}}\right) = \pi + \mathcal{O}(10^{-2}),$$

leading to

$$\alpha^{\rm SM} + \beta^{\rm SM} + \gamma^{\rm SM} \approx \pi, \quad \beta'^{\rm SM} \approx 0.$$

However, from we learn that *model-independently*,

$$\alpha + \beta + \gamma - \beta' = 0 (\mathrm{mod}\ \pi).$$

Then, obviously, $\alpha+\beta+\gamma = \pi$ is equivalent to $\beta' = 0$. The sum of the three angles that in the SM correspond to angles of the unitarity triangle will be consistent with π if the CP asymmetries in B_s decays into final CP eigenstates through $b \to c\bar{c}s$ vanish. This is independent of the mechanism of $B^0 - \bar{B}^0$ mixing and of whether α, β, γ are related to angles of the unitarity triangle.

Two ingredients of the Standard Model are in the basis of the prediction that $a_{CP}(B_s \to D_s^+ D_s^-) \approx 0$. First, that B_s mixing is dominated by box diagrams with intermediate top quarks. Second, that CKM unitarity (and the smallness of $|V_{ub}V_{us}|$) implies $V_{tb}V_{ts}^* + V_{cb}V_{cs}^* \approx 0$. As argued in [], a violation of this unitarity relation always implies large new contributions to B_s mixing, either from box diagrams with t' (if violation of CKM unitarity comes from a 4th generation) or from Z-mediated tree diagrams (if the violation is due to a non-sequential quark). Thus, if is violated, then clearly there is a significant new contribution to B_s mixing. It is possible that, in addition, CKM unitarity is violated, but that can be tested independently [].

Ackowledgments

I am grateful to Guy Blaylock and Abe Seiden for a very enjoyable collaboration on the question of CP violation in $D-\bar{D}$ mixing. I thank Sandip Pakvasa for very useful discussions during the conference and for informing me on his work in preparation with Tom Browder. This work was supported in part by the United States – Israel Binational Science Foundation (BSF), by the Israel Commission for Basic Research and by the Minerva Foundation.