Lessons from BaBar and Belle measurements of $D^0 - \overline{D^0}$ mixing parameters

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ABSTRACT: The BaBar and Belle experiments have recently presented evidence for $D^0 - \overline{D^0}$ mixing. We explain the following points: (i) The measurements imply width difference $y \sim 0.01$. In the limit of small CP violation, the CP-odd state is longer-lived; (ii) $y \sim 0.01$ is consistent with the Standard Model. It suggests that SU(3) breaking from phase space effects is likely to play a major role; (iii) There is no evidence for either large mass splitting or CP violation. Consequently, there is no hint for new physics; (iv) The stronger bounds on the mass splitting and on CP violation imply that, if squarks are observed at the LHC, it is unlikely that they will be non-degenerate.

KEYWORDS: Supersymmetry Phenomenology, Weak Decays, Beyond Standard Model, CP violation.

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Contents

1. Introduction

Neutral meson mixing has been observed in all down-type neutral meson systems (K, B and B_s) providing a sensitive probe of the flavor structure of the Standard Model and its extensions. In contrast, mixing in the neutral D-meson system (the *only* up-type neutral meson) has not been observed until very recently. This situation is now changed. Measurements of the doubly Cabibbo suppressed (DCS) $D^0 \to K^+\pi^-$ decay by the BaBar experiment [1], and of the singly Cabibbo suppressed (SCS) $D^0 \to K^+K^-, \pi^+\pi^-$ decays by the Belle experiment [2], have given evidence of width difference between the two neutral D-meson mass eigenstates:

$$y' \cos\phi = (0.97 \pm 0.44 \pm 0.31) \times 10^{-2}, \qquad (1.1)$$

$$y_{\mathrm{CP}} = (1.31 \pm 0.32 \pm 0.25) \times 10^{-2}. \qquad (1.2)$$

In this note we explain the significance of these results.

In section 2 we present the formalism of DCS and SCS neutral D decays, and the simplifications that follow from neglecting direct CP violation. In section 3 we interpret the new results qualitatively and quantitatively and explain their implications for width difference, mass difference, CP violation and strong phases in the neutral D-meson system. In section 4 we examine the implications of the new results for the Standard Model, and to models of new physics, particularly supersymmetry with alignment. We summarize our conclusions in section 5. We collect new and previous relevant experimental results and derive world averages in appendix A.

2. Formalism

In this section, we present the formalism that describes the neutral D decay and mixing, following the analysis of ref. [3]. The two neutral D-meson mass eigenstates, $|D_1\rangle$ of mass m_1 and width Γ_1 and $|D_2\rangle$ of mass m_2 and width Γ_2 are linear combinations of the interaction eigenstates D^0 (with quark content $c\overline{u}$) and $\overline{D^0}$ (with quark content $\overline{c}u$):

$$
\begin{aligned}
|D_1\rangle &= p|D^0\rangle + q|\overline{D^0}\rangle, \\
|D_2\rangle &= p|D^0\rangle - q|\overline{D^0}\rangle.
\end{aligned} \tag{2.1}
$$

The average and the difference in mass and width are given by

$$
\begin{aligned}
m &\equiv \frac{m_1 + m_2}{2}, \qquad \Gamma \equiv \frac{\Gamma_1 + \Gamma_2}{2}, \\
x &\equiv \frac{m_2 - m_1}{\Gamma}, \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}.
\end{aligned} \tag{2.2}
$$

The decay amplitudes into a final state f are defined as follows:

$$
\begin{aligned}
A_f &= \langle f|\mathcal{H}|D^0\rangle, \\
\overline{A}_f &= \langle f|\mathcal{H}|\overline{D^0}\rangle.
\end{aligned} \tag{2.3}
$$

We define λ_f:

$$
\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}. \tag{2.4}
$$

We now write the approximate expressions for the time-dependent DCS and SCS decay rates that are valid for time $t \lesssim 1/\Gamma$. We take into account the experimental information that x, y and $\tan\theta_c$ (where θ_c is the Cabibbo angle) are small, and expand each of the rates only to the order that is relevant to the BaBar and Belle measurements:

$$
\begin{aligned}
\Gamma[D^0(t) \to K^+\pi^-] &= e^{-\Gamma t}|\overline{A}_{K^+\pi^-}|^2|q/p|^2 \\
&\quad \times \left\{ |\lambda_{K^+\pi^-}^{-1}|^2 + [\mathcal{R}e(\lambda_{K^+\pi^-}^{-1})y + \mathcal{I}m(\lambda_{K^+\pi^-}^{-1})x]\Gamma t + \frac{1}{4}(y^2+x^2)(\Gamma t)^2 \right\}, \\
\Gamma[\overline{D^0}(t) \to K^-\pi^+] &= e^{-\Gamma t}|A_{K^-\pi^+}|^2|p/q|^2 \\
&\quad \times \left\{ |\lambda_{K^-\pi^+}|^2 + [\mathcal{R}e(\lambda_{K^-\pi^+})y + \mathcal{I}m(\lambda_{K^-\pi^+})x]\Gamma t + \frac{1}{4}(y^2+x^2)(\Gamma t)^2 \right\},
\end{aligned} \tag{2.5}
$$

$$
\begin{aligned}
\Gamma[D^0(t) \to K^+K^-] &= e^{-\Gamma t}|A_{K^+K^-}|^2 \left\{ 1 + [\mathcal{R}e(\lambda_{K^+K^-})y - \mathcal{I}m(\lambda_{K^+K^-})x]\Gamma t \right\}, \\
\Gamma[\overline{D^0}(t) \to K^+K^-] &= e^{-\Gamma t}|\overline{A}_{K^+K^-}|^2 \left\{ 1 + [\mathcal{R}e(\lambda_{K^+K^-}^{-1})y - \mathcal{I}m(\lambda_{K^+K^-}^{-1})x]\Gamma t \right\}.
\end{aligned} \tag{2.6}
$$

Within the Standard Model, the physics of $D^0 - \overline{D^0}$ mixing and of the tree level decays is dominated by the first two generations and, consequently, CP violation can be safely neglected (for reviews of charm physics, see [4, 5]). Indeed, CP violation in these processes would constitute a signal for new physics [6, 7, 3]. In all 'reasonable' extensions of the Standard Model, both the DCS [8] and the SCS [9] decays are still dominated by the Standard Model CP conserving contributions. On the other hand, there could be new short

distance, possibly CP violating contributions to the mixing amplitude M_{12}. Allowing for only such CP violating effects of new physics, the picture of CP violation is simplified since there is no direct CP violation.[1] The effects of indirect CP violation can be parametrized in the following way [10]:

$$
\begin{aligned}
\lambda_{K^+\pi^-}^{-1} &= r_d|p/q|e^{-i(\delta+\phi)}, \\
\lambda_{K^-\pi^+} &= r_d|q/p|e^{-i(\delta-\phi)}, \\
\lambda_{K^+K^-} &= -|q/p|e^{i\phi},
\end{aligned}
\tag{2.7}
$$

where r_d is a real and positive dimensionless parameter, δ is a strong (CP conserving) phase, and ϕ is a weak (CP violating) phase. The appearance of a single weak phase common to all final states is related to the absence of direct CP violation, while the absence of a strong phase in $\lambda_{K^+K^-}$ is related to the fact that the final state is a CP eigenstate. CP violation in mixing is related to

$$
A_m \equiv \frac{|q/p|^2 - 1}{|q/p|^2 + 1} \neq 0.
\tag{2.8}
$$

CP violation in the interference of decays with and without mixing is related to $\sin\phi \neq 0$. In the limit of CP conservation, where the mass eigenstates are also CP eigenstates, choosing $\phi = 0$ is equivalent to defining $|D_1\rangle = |D_-\rangle$ and $|D_2\rangle = |D_+\rangle$, with $D_-(D_+)$ being the CP-odd (CP-even) state, that is, the state that does not (does) decay into K^+K^-. (Alternatively, $\phi = \pi$ is also a legitimate choice in the CP conserving case; it simply identifies $|D_1\rangle = |D_+\rangle$ and $|D_2\rangle = |D_-\rangle$. The physical observable $y\cos\phi$ remains unchanged under these alternative conventions.)

For the analysis of the DCS decays, it is convenient to further define

$$
\begin{aligned}
x' &\equiv x\cos\delta + y\sin\delta, \\
y' &\equiv y\cos\delta - x\sin\delta.
\end{aligned}
\tag{2.9}
$$

In the absence of direct CP violation, the expressions for the DCS decay rates (2.5) and for the SCS decay rates (2.6) simplify:

$$
\begin{aligned}
\Gamma[D^0(t) \to K^+\pi^-] &= e^{-\Gamma t}|A_{K^-\pi^+}|^2 \\
&\times \left[r_d^2 + r_d|q/p|(y'\cos\phi - x'\sin\phi)\Gamma t + \frac{1}{4}|q/p|^2(y^2+x^2)(\Gamma t)^2\right], \\
\Gamma[\overline{D^0}(t) \to K^-\pi^+] &= e^{-\Gamma t}|A_{K^-\pi^+}|^2 \\
&\times \left[r_d^2 + r_d|p/q|(y'\cos\phi + x'\sin\phi)\Gamma t + \frac{1}{4}|p/q|^2(y^2+x^2)(\Gamma t)^2\right], \\
\Gamma[D^0(t) \to K^+K^-] &= e^{-\Gamma t}|A_{K^+K^-}|^2\left[1 - |q/p|(y\cos\phi - x\sin\phi)\Gamma t\right], \\
\Gamma[\overline{D^0}(t) \to K^+K^-] &= e^{-\Gamma t}|A_{K^+K^-}|^2\left[1 - |p/q|(y\cos\phi + x\sin\phi)\Gamma t\right].
\end{aligned}
$$
(2.10) (2.11)

---

[1]In some supersymmetric models, SCS decays may exhibit comparable direct and indirect CP violations [9].

Ref. [1] uses parameters $y'_\pm$ and $x'^2_\pm$ that correspond to the following combinations of parameters:

$$y'_+ = |q/p|(y'\cos\phi - x'\sin\phi), \qquad x'_+ = |q/p|(x'\cos\phi + y'\sin\phi),$$
$$y'_- = |p/q|(y'\cos\phi + x'\sin\phi), \qquad x'_- = |p/q|(x'\cos\phi - y'\sin\phi). \tag{2.12}$$

In the limit of CP conservation,

$$y'_+ = y'_- \equiv y'_0 = \left(\frac{\Gamma_+ - \Gamma_-}{2\Gamma}\right)\cos\delta - \left(\frac{m_+ - m_-}{\Gamma}\right)\sin\delta,$$
$$x'_+ = x'_- \equiv x'_0 = \left(\frac{\Gamma_+ - \Gamma_-}{2\Gamma}\right)\sin\delta + \left(\frac{m_+ - m_-}{\Gamma}\right)\cos\delta, \tag{2.13}$$

where sub-indices $+(-)$ in $\Gamma_\pm$ and $m_\pm$ denote the CP-even (-odd) mass eigenstate.

Ref. [2] uses parameters $y_{\rm CP}$ and A_Γ that correspond to the following combinations of parameters:[2]

$$y_{\rm CP} = \frac{1}{2}(|q/p| + |p/q|)y\cos\phi - \frac{1}{2}(|q/p| - |p/q|)x\sin\phi, \tag{2.14}$$

$$A_\Gamma = \frac{1}{2}(|q/p| - |p/q|)y\cos\phi - \frac{1}{2}(|q/p| + |p/q|)x\sin\phi. \tag{2.15}$$

In the limit of CP conservation,

$$y_{\rm CP} = \frac{\Gamma_+ - \Gamma_-}{2\Gamma},$$
$$A_\Gamma = 0. \tag{2.16}$$

3. Interpreting the data (model independently)

Ref. [2] gives the following results related to the SCS decays:

$$y_{\rm CP} = (1.31 \pm 0.32 \pm 0.25) \times 10^{-2}, \tag{3.1}$$
$$A_\Gamma = (0.01 \pm 0.30 \pm 0.15) \times 10^{-2}. \tag{3.2}$$

Two straightforward statements follow from eqs. (3.1) and (3.2):

- There is evidence for $D^0 - \overline{D^0}$ mixing;

- There is no evidence for CP violation in $D^0 - \overline{D^0}$ mixing.

We would like to be more quantitative on the issue of CP violation. If we make the plausible assumption that $y_{\rm CP}$ is dominated by the y-term (note that the x-term has two CP violating factors, while the y-term has none), then the ratio $A_\Gamma/y_{\rm CP}$ is very informative:

$$\frac{A_\Gamma}{y_{\rm CP}} \approx A_m - \frac{x}{y}\tan\phi. \tag{3.3}$$

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[2]In the notations of the PDG [11], $y_{\rm CP} \equiv Y$ and $A_\Gamma \equiv -\Delta Y$.

It will be helpful if experiments quote their results directly for this ratio. We assume that the systematic errors in eqs. (3.1), (3.2) cancel in this ratio. Then we obtain the following constraint on CP violation:

$$A_m - \frac{x}{y} \tan \phi \sim 0.0 \pm 0.3. \tag{3.4}$$

There could be cancellations between the two terms in eq. (3.4). Furthermore, at the $2-3\sigma$ level, CP violation could still be large. Yet, barring fine-tuned cancellations, the results are suggestive (at the $1 - 2\sigma$ level) that $|q/p| \approx 1$ and either $|\sin \phi| < 1$ or $|x| < |y|$ (or both). If the correct interpretation of (3.2) is indeed that CP violation is small, then (3.1) reads

$$\frac{\Gamma_+ - \Gamma_-}{2\Gamma} \approx (+1.3 \pm 0.4) \times 10^{-2}. \tag{3.5}$$

To summarize, the Belle results are suggestive of the following statements regarding $D^0 - \overline{D^0}$ mixing:

- The width difference is of order one percent;

- The CP-odd state is longer-lived;

- CP violation in mixing is small;

- Either the mass difference is smaller than the width difference, or CP violation in the interference of decays with and without mixing is small, or both.

Ref. [1] gives the following results related to the DCS decays:[3]

$$y'_+ = (0.98 \pm 0.64 \pm 0.45) \times 10^{-2},$$
$$y'_- = (0.96 \pm 0.61 \pm 0.43) \times 10^{-2},$$
$$x'^2_+ = (-2.4 \pm 4.3 \pm 3.0) \times 10^{-4},$$
$$x'^2_- = (-2.0 \pm 4.1 \pm 2.9) \times 10^{-4}. \tag{3.6}$$

The fact that the results are consistent with $y'_+ = y'_-$ means that also here there is no evidence for CP violation. Making the plausible assumption that $y'_{\pm}$ are dominated by the $y' \cos \phi$ terms, then the ratio $(y'_+ - y'_-)/(y'_+ + y'_-)$ can be simply interpreted:

$$\frac{y'_+ - y'_-}{y'_+ + y'_-} \approx A_m - \frac{x'}{y'} \tan \phi. \tag{3.7}$$

Again, it will be helpful if experiments quote their results directly for this ratio. We assume that the systematic errors in eqs. (3.6) cancel in this ratio. We further assume that there are no fine-tuned cancellations between the two terms in eq. (3.7). Then we obtain upper bounds on CP violation that are somewhat weaker than eq. (3.4), namely $A_m - (x'/y') \tan \phi \sim 0.0 \pm 0.6$.

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[3]Ref. [1] allows for direct CP violation in their fit. The results are, however, consistent with vanishing direct CP violation. We therefore use our formalism which neglects direct CP violation.

Neglecting CP violation, ref. [1] obtains the following fit:

$$y'_0 = (0.97 \pm 0.54) \times 10^{-2}, \tag{3.8}$$

$$x'^2_0 = (-2.2 \pm 3.7) \times 10^{-4}. \tag{3.9}$$

where $y'_0 = y$ for $\phi = 0$ [see eq. (2.13)]. Taking into account the strong correlation between these two observables, BaBar finds that the possibility of no mixing is disfavored at the 3.9 standard deviations. It is interesting to note, however, that Belle finds [12], for the CP conserving case, $y'_0 = (0.06 \pm 0.40) \times 10^{-2}$. The average of the two results for y'_0 (see appendix A) does not show evidence for mixing, but one must remember that this simple averaging does not keep the correlation information.

The results on SCS and DCS decays cannot be combined in a straightforward way, because of the presence of strong phases in the $D \to K\pi$ decays. Only if one assumes that the strong phase is small, one can interpret the BaBar result in terms of y. Indeed, $\delta = 0$ in the flavor SU(3) limit, but it is not clear whether the relevant SU(3) breaking effects are small [13, 14] or large [15]. In any case, as long as $\delta < \pi/2$, the BaBar result is also suggestive that the CP-even state has a shorter lifetime.

As concerns experimental information on the strong phase δ, a preliminary CLEO result gives [16]

$$\cos\delta = 1.09 \pm 0.66. \tag{3.10}$$

The new experimental results can be used to get further idea about δ. Following [3], we approximate $|q/p|^2 = 1$ and $|\sin\phi| = 0$ and combine (2.9) and (2.14) to get

$$\frac{y' \cos\phi}{y_{CP}} = \cos\delta - \frac{x}{y}\sin\delta. \tag{3.11}$$

If we consider only the recent Belle result for y_{CP} and BaBar result for $y' \cos\phi$, we obtain

$$+0.74 \pm 0.47 = \cos\delta - (x/y)\sin\delta. \tag{3.12}$$

For $|x| \ll |y|$ we have $|\delta| \lesssim 5\pi/12$. For $x \sim -y$, the preferred ranges are around $\delta \sim 0$ or $\delta \sim \pi/2$ while for $x \sim +y$, the preferred ranges are around $\delta \sim 0$ or $\delta \sim 3\pi/2$. In all cases, the results are consistent with $\delta = 0$. On the other hand, if we use the world averages (A.2) for y_{CP} and (A.6) for $y' \cos\phi$, then the range for the left hand side is lower, roughly 0.2 ± 0.2, and $\delta = 0$ (or, more generally, $\cos\delta \gtrsim 0.9$) is disfavored. We conclude that more data is needed to clarify the situation regarding the strong phase.

4. Implications for models

4.1 The standard model

Because of the GIM mechanism, the mixing amplitude is proportional to differences of terms suppressed by $m^2_{d,s,b}/m^2_W$, and so $D^0 - \overline{D^0}$ is very slow in the Standard Model (for a survey of predictions, see [17, 18]). The contribution of the b quark is further suppressed by the small CKM elements $|V_{ub}V^*_{cb}|^2/|V_{us}V^*_{cs}|^2 = \mathcal{O}(10^{-6})$, and can be neglected. Thus,

the D system essentially involves only the first two generations, and therefore CP violation is absent both in the mixing amplitude and in the dominant tree-level decay amplitudes. Once the contribution of the b quark is neglected, the mixing vanishes in the flavor SU(3) limit and, if SU(3) breaking can be treated analytically, it only arises at second order in SU(3) breaking [19, 20]:

$$x, y \sim \sin^2 \theta_c \times [SU(3) \text{ breaking}]^2. \tag{4.1}$$

Precise calculations of x and y in the Standard Model are not possible at present, because the charm mass is neither heavy enough to justify inclusive calculations [21–23], nor is it light enough to allow a few exclusive channels to give a reliable estimate [24–29]. Most studies (particularly the 'inclusive' ones) find $x, y \lesssim 10^{-3}$. Ref. [23] raises the possibility that x, y will be measured at the 10^{-2} level, interpreting such a result as breakdown of the OPE.

According to eq. (4.1), computing x and y in the Standard Model requires a calculation of SU(3) violation in decay rates. There are many sources of SU(3) violation, most of them involving nonperturbative physics in an essential way. In ref. [19], SU(3) breaking arising from phase space differences was studied; computing them in two-, three-, and four-body D decays, it was found that y could naturally be at the level of one percent. The result can be traced back to the fact that the SU(3) cancellation between the contributions of members of the same multiplet can be badly broken when decays to the heaviest members of a multiplet have a small or vanishing phase space. This effect is manifestly not included in the OPE-based calculations of $D^0 - \overline{D^0}$ mixing, which cannot address threshold effects. The experimental results, implying $y = \mathcal{O}(0.01)$, suggest that the phase space effect analyzed in ref. [19] is, very likely, a significant if not the dominant source of the width splitting. In particular, there is no significant cancellation against other sources of SU(3) breaking.

If the dominant SU(3) breaking mechanism is indeed the one studied in ref. [19], should we expect x to be comparably large? The task of answering this question was taken in ref. [20]. The Standard Model prediction for x/y due to SU(3) breaking from final state phase space differences was studied. A dispersion relation relating Δm to $\Delta \Gamma$ using Heavy Quark Effective Theory (HQET) was derived. The calculation is less model independent than the one of y [19], and should be trusted only at the order of magnitude level. The final conclusion was that, if y is dominated by the four body decays considered in [19], we should expect $|x|$ between 10^{-3} and 10^{-2}, and that x and y are of opposite signs.

We conclude that the evidence for $y \sim 0.01$, the upper bound on $x \lesssim 0.02$, and the absence of signals of CP violation are all very consistent with the Standard Model. The value of y implies large SU(3) breaking effects, of just the right size to be accounted for by phase space effects identified in [19].

4.2 Beyond the standard model

New physics modifies the $\Delta C = 2$ part in the $D^0 - \overline{D^0}$ mixing amplitude, M_{12}^D. It could give mixing that is close to the experimental bound. This situation is unavoidable in supersymmetric models where the only flavor suppression mechanism is alignment [30–32]. Hence, it is important to find the precise limit on M_{12}^D.

In terms of measurable quantities, $|M_{12}^D|$ is given by [33, 34]

$$|M_{12}^D|^2 = \left(\frac{x\Gamma}{2}\right)^2 \frac{1 + A_m^2(y/x)^2}{1 - A_m^2}. \tag{4.2}$$

The strongest bound would apply in the CP conserving case, $|q/p| = 1$, in which case $|M_{12}^D| = |x|\Gamma/2$. Using the new Belle result of eq. (A.10) to obtain an upper bound $|x| \lesssim 0.015$ (95% C.L.), we get

$$|M_{12}^D| \lesssim 1.2 \times 10^{-11} \ MeV \quad \text{(CP conservation)}, \tag{4.3}$$

a factor of two stronger than [34]. The bound becomes, however, weaker in the presence of CP violation in mixing. If we take $A_m^2 \lesssim 0.3$ [see eq. (3.4)], then the bound is relaxed by a factor ~ 2:

$$|M_{12}^D| \lesssim 2.2 \times 10^{-11} \ MeV \quad \text{(CP violation)}, \tag{4.4}$$

a factor of three stronger than [34]. A numerical fit of the five relevant parameters $(y, x, \delta, \phi, |q/p|)$ to the six observables $(y_{CP}, A_\Gamma, y'_\pm, x'_\pm)$ will give more accurate results. It will be useful, however, for the purpose of such fit, if experiments quote the errors directly on the CP violating ratios (3.3) and (3.7).

When the bound on $|M_{12}^D|$ is strengthened by a factor ~ 3, the bound on the relevant flavor changing supersymmetric parameter $(\delta_{LL}^u)_{12}$ is strengthened by a factor $\sim \sqrt{3}$. Barring accidental cancellations between the Standard Model and the supersymmetric contribution, or between various terms in the supersymmetric contribution (these appear for a certain ratio between the squark and the gluino masses), or RGE-induced approximate degeneracy [32], this stronger bound can be translated into a lower bound on the scale of gluino and up-squark masses of order $2\,\text{TeV}$, which is uncomfortably high.

Alignment models have provided the only natural example of models with a squark spectrum that is potentially both light and non-degenerate. Consequently, the lessons from the new constraints can be stated as follows:

- If squark masses are within the reach of the LHC, it is very unlikely that they will show no degeneracy.

- If such a situation is nevertheless realized in Nature, it requires a specific relation between the up-squark and gluino mass [32] or accidental strong cancellations between the Standard Model and the supersymmetric contributions.

5. Conclusions

- Evidence for for $D^0 - \overline{D^0}$ mixing has been achieved by the Belle experiment [2], in the singly Cabibbo (SCS) suppressed $D \to K^+K^-, \pi^+\pi^-$ decay modes, and by the BaBar experiment [1], in the doubly Cabibbo suppressed (DCS) $D \to K\pi$ decay mode.

- When combined with previous results from other experiments, the signal for $y_{CP} \neq 0$ in the SCS decay is strengthened (to about 4σ).

- The evidence implies a width difference at the one percent level. In the limit of small CP violation, the CP-odd state is longer-lived ($|D_-\rangle = |D_L\rangle$, $|D_+\rangle = |D_S\rangle$).

- There is no evidence for either mass splitting or CP violation.

- A width difference $y \sim 0.01$ is consistent with the Standard Model. In particular, it suggests that SU(3) breaking from phase space effects, identified and calculated in ref. [19], are likely to play a major role. In that case, x should be not far below present bounds [20].

- The fact that $|x/y| > 1$ seems to be disfavored, and that there is not even a hint to CP violation, implies that there is no hint for new physics.

- The stronger bounds on x and on A_m imply that supersymmetric models of alignment are viable only if (i) there is some level of squark degeneracy from RGE, and/or (ii) the squark and gluino masses are heavier than $2\,\mathrm{TeV}$, and/or (iii) there is accidental cancellation between various supersymmetric diagrams. The likelihood of observing light non-degenerate squarks at the LHC became considerably lower.

Mixing, CP violation in mixing, and CP violation in the interference of decays with and without mixing, should affect all neutral D-meson decays to final states that are common to D^0 and $\overline{D^0}$. Thus, the picture that is now emerging — $y \sim 0.01$, $|x| \lesssim |y|$ and small or zero CP violation — can be further tested and sharpened by additional experimental results.

While this paper was being written, a related study appeared [35].

Acknowledgments

A. Experimental results

In addition to the new experimental results that give evidence for $D^0 - \overline{D^0}$ mixing, there is additional data that has not given such evidence. We here present the relevant data, and combine it with the new results to obtain world averages.

The experimental results on y_{CP} are the following:

$$y_{CP} = \begin{cases} (3.42 \pm 1.39 \pm 0.74) \times 10^{-2} & \text{FOCUS [36]} \\ (0.8 \pm 2.9 \pm 1.0) \times 10^{-2} & \text{E791 [37]} \\ (-1.2 \pm 2.5 \pm 1.4) \times 10^{-2} & \text{CLEO [38]} \\ (0.8 \pm 0.4^{+0.5}_{-0.4}) \times 10^{-2} & \text{BaBar [39]} \\ (1.31 \pm 0.30 \pm 0.25) \times 10^{-2} & \text{Belle [2]} \end{cases} \qquad (A.1)$$

leading to world average of

$$y_{CP} = (+1.20 \pm 0.31) \times 10^{-2}. \qquad (A.2)$$

Thus, the evidence for $y_{CP} \neq 0$ is strengthened by other experiments, and the world average gives it a 4σ significance.

The experimental results on $\Delta Y (= -A_\Gamma)$ are the following:

$$\Delta Y = \begin{cases} (-0.8 \pm 0.6 \pm 0.2) \times 10^{-2} & \text{BaBar [39]} \\ (-0.01 \pm 0.30 \pm 0.15) \times 10^{-2} & \text{Belle [2]} \end{cases} \qquad (A.3)$$

leading to world average of

$$\Delta Y = (-0.21 \pm 0.30) \times 10^{-2}. \qquad (A.4)$$

The experimental results on $y_0' = y' \cos \phi$, assuming CP conservation, are the following:[4]

$$y_0' = \begin{cases} (-23 \pm 14 \pm 3) \times 10^{-3} & \text{CLEO [42]} \\ (0.6^{+4.0}_{-3.9}) \times 10^{-3} & \text{Belle [12]} \\ (9.7 \pm 4.4 \pm 3.1) \times 10^{-3} & \text{BaBar [1]} \end{cases} \qquad (A.5)$$

leading to world average of

$$y_0' = (2.5 \pm 3.1) \times 10^{-3}. \qquad (A.6)$$

Thus, the data from other experiments (particularly the lower range measured by Belle) weaken the signal for $y' \neq 0$ to below one sigma. Note, however, that the information on the correlation between y' and x' is lost in this simple averaging.

The experimental results on $x_0'^2$, assuming CP conservation, are the following:

$$x_0'^2 = \begin{cases} (1.8^{+2.1}_{-2.3}) \times 10^{-4} & \text{Belle [12]} \\ (-2.2 \pm 3.0 \pm 2.1) \times 10^{-4} & \text{BaBar [1]} \end{cases} \qquad (A.7)$$

leading to world average of

$$x'^2 = (0.7 \pm 1.9) \times 10^{-4}. \qquad (A.8)$$

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[4]We do not include the results of E791 [40] and FOCUS [41] which are not given in a form appropriate for our purposes.

If we interpret this bound as $|x'| = (0.8 \pm 0.8) \times 10^{-2}$, and combine that with the CLEO result [42] $|x'| = (0.0 \pm 1.5 \pm 0.2) \times 10^{-2}$, we obtain

$$|x'| = (0.6 \pm 0.7) \times 10^{-2}. \tag{A.9}$$

Finally, we mention significant new (preliminary) results [43] on a Dalitz plot analysis that yields

$$x = (0.80 \pm 0.29 \pm 0.17) \times 10^{-2},$$
$$y = (0.33 \pm 0.24 \pm 0.15) \times 10^{-2}. \tag{A.10}$$

References

[1] BABAR collaboration, B. Aubert et al., *Evidence for D^0-$\bar{D}^0$ mixing*, hep-ex/0703020.

[2] BELLE collaboration, M. Staric et al., *Evidence for $D^0 - \bar{D}^0$ mixing*, hep-ex/0703036.

[3] S. Bergmann, Y. Grossman, Z. Ligeti, Y. Nir and A.A. Petrov, *Lessons from CLEO and focus measurements of D^0-$\bar{D}^0$ mixing parameters*, *Phys. Lett.* **B 486** (2000) 418 [hep-ph/0005181].

[4] S. Bianco, F.L. Fabbri, D. Benson and I. Bigi, *A cicerone for the physics of charm*, *Nuovo Cim.* **26** (2003) 1 [hep-ex/0309021].

[5] G. Burdman and I. Shipsey, *D^0-$\bar{D}^0$ mixing and rare charm decays*, *Ann. Rev. Nucl. Part. Sci.* **53** (2003) 431 [hep-ph/0310076].

[6] I.I.Y. Bigi and A.I. Sanda, *On D^0-$\bar{D}^0$ mixing and CP-violation*, *Phys. Lett.* **B 171** (1986) 320;
I.I. Bigi, in: *Proceed. of the Tau-Charm Workshop*, L.V. Beers (ed.), SLAC-Report-343 (1989).

[7] G. Blaylock, A. Seiden and Y. Nir, *The role of CP-violation in D^0-$\bar{D}^0$ mixing*, *Phys. Lett.* **B 355** (1995) 555 [hep-ph/9504306].

[8] S. Bergmann and Y. Nir, *New physics effects in doubly Cabibbo suppressed D decays*, *JHEP* **09** (1999) 031 [hep-ph/9909391].

[9] Y. Grossman, A.L. Kagan and Y. Nir, *New physics and CP-violation in singly Cabibbo suppressed D decays*, *Phys. Rev.* **D 75** (2007) 036008 [hep-ph/0609178].

[10] Y. Nir, *CP-violation in and beyond the standard model*, hep-ph/9911321.

[11] D. Kirkby and Y. Nir, *Review on CP violation in meson decays*, in W.M. Yao et al., PARTICLE DATA GROUP collaboration, *Review of particle physics*, *J. Phys.* **G 33** (2006) 1.

[12] BELLE collaboration, L.M. Zhang et al., *Improved constraints on D^0-$\bar{D}^0$ mixing in $D^0 \to K^+\pi^-$ decays at Belle*, *Phys. Rev. Lett.* **96** (2006) 151801 [hep-ex/0601029].

[13] L.-L. Chau and H.-Y. Cheng, *SU(3) breaking effects in charmed meson decays*, *Phys. Lett.* **B 333** (1994) 514 [hep-ph/9404207].

[14] T.E. Browder and S. Pakvasa, *Experimental implications of large CP-violation and final state interactions in the search for D^0-$\bar{D}^0$ mixing*, *Phys. Lett.* **B 383** (1996) 475 [hep-ph/9508362].

[15] A.F. Falk, Y. Nir and A.A. Petrov, *Strong phases and D^0-$\bar{D}^0$ mixing parameters*, *JHEP* **12** (1999) 019 [hep-ph/9911369].

[16] CLEO collaboration, D.M. Asner et al., D^0-$\bar{D}^0$ *quantum correlations, mixing and strong phases*, *Int. J. Mod. Phys.* **A 21** (2006) 5456 [`hep-ex/0607078`].

[17] H.N. Nelson, *Compilation of $D_0 \to \bar{D}_0$ mixing predictions*, `hep-ex/9908021`.

[18] A.A. Petrov, *Charm mixing in the standard model and beyond*, *Int. J. Mod. Phys.* **A 21** (2006) 5686 [`hep-ph/0611361`].

[19] A.F. Falk, Y. Grossman, Z. Ligeti and A.A. Petrov, SU(3) *breaking and D^0-$\bar{D}^0$ mixing*, *Phys. Rev.* **D 65** (2002) 054034 [`hep-ph/0110317`].

[20] A.F. Falk, Y. Grossman, Z. Ligeti, Y. Nir and A.A. Petrov, *The D^0-$\bar{D}^0$ mass difference from a dispersion relation*, *Phys. Rev.* **D 69** (2004) 114021 [`hep-ph/0402204`].

[21] H. Georgi, *D-anti-D mixing in heavy quark effective field theory*, *Phys. Lett.* **B 297** (1992) 353 [`hep-ph/9209291`].

[22] T. Ohl, G. Ricciardi and E.H. Simmons, *D-anti-D mixing in heavy quark effective field theory: the sequel*, *Nucl. Phys.* **B 403** (1993) 605 [`hep-ph/9301212`].

[23] I.I.Y. Bigi and N.G. Uraltsev, D^0-$\bar{D}^0$ *oscillations as a probe of quark-hadron duality*, *Nucl. Phys.* **B 592** (2001) 92 [`hep-ph/0005089`].

[24] J.F. Donoghue, E. Golowich, B.R. Holstein and J. Trampetic, *Dispersive effects in D^0-$\bar{D}^0$ mixing*, *Phys. Rev.* **D 33** (1986) 179.

[25] F. Buccella, M. Lusignoli and A. Pugliese, *Charm nonleptonic decays and final state interactions*, *Phys. Lett.* **B 379** (1996) 249 [`hep-ph/9601343`].

[26] E. Golowich and A.A. Petrov, *Can nearby resonances enhance D^0-$\bar{D}^0$ mixing?*, *Phys. Lett.* **B 427** (1998) 172 [`hep-ph/9802291`].

[27] L. Wolfenstein, D^0-$\bar{D}^0$ *mixing*, *Phys. Lett.* **B 164** (1985) 170.

[28] P. Colangelo, G. Nardulli and N. Paver, *On D^0-$\bar{D}^0$ mixing in the standard model*, *Phys. Lett.* **B 242** (1990) 71.

[29] T.A. Kaeding, *D meson mixing in broken* SU(3), *Phys. Lett.* **B 357** (1995) 151 [`hep-ph/9505393`].

[30] Y. Nir and N. Seiberg, *Should squarks be degenerate?*, *Phys. Lett.* **B 309** (1993) 337 [`hep-ph/9304307`].

[31] M. Leurer, Y. Nir and N. Seiberg, *Mass matrix models: the sequel*, *Nucl. Phys.* **B 420** (1994) 468 [`hep-ph/9310320`].

[32] Y. Nir and G. Raz, *Quark squark alignment revisited*, *Phys. Rev.* **D 66** (2002) 035007 [`hep-ph/0206064`].

[33] G.C. Branco, L. Lavoura and J.P. Silva, *CP violation*, Clarendon Press, Oxford (1999).

[34] G. Raz, *Interpreting experimental bounds on D^0-$\bar{D}^0$ mixing in the presence of CP-violation*, *Phys. Rev.* **D 66** (2002) 057502 [`hep-ph/0205113`].

[35] M. Ciuchini et al., *D-dbar mixing and new physics: general considerations and constraints on the MSSM*, `hep-ph/0703204`.

[36] FOCUS collaboration, J.M. Link et al., *A measurement of lifetime differences in the neutral D meson system*, *Phys. Lett.* **B 485** (2000) 62 [`hep-ex/0004034`].

[37] E791 collaboration, A.J. Schwartz, *CP-violation and mixing results from FNAL E791*, *Nucl. Phys.* **99B** *(Proc. Suppl.)* (2001) 276 [`hep-ex/0012006`].

[38] CLEO collaboration, S.E. Csorna et al., *Lifetime differences, direct CP-violation and partial widths in D^0 meson decays to K^+K^- and $\pi^+\pi^-$*, *Phys. Rev.* **D 65** (2002) 092001 [`hep-ex/0111024`].

[39] BABAR collaboration, B. Aubert et al., *Limits on $D^0\bar{D}^0$ mixing and CP-violation from the ratio of lifetimes for decay to $K^-\pi^+$, K^-K^+ And $\pi^-\pi^+$*, *Phys. Rev. Lett.* **91** (2003) 121801 [`hep-ex/0306003`].

[40] E791 collaboration, E.M. Aitala et al., *A search for D^0-$\bar{D}^0$ mixing and doubly-Cabibbo-suppressed decays of the D_0 in hadronic final states*, *Phys. Rev.* **D 57** (1998) 13 [`hep-ex/9608018`].

[41] FOCUS collaboration, J.M. Link et al., *Measurement of the doubly cabibbo suppressed decay $D_0 \to K^+\pi^-$ and a search for charm mixing*, *Phys. Lett.* **B 618** (2005) 23 [`hep-ex/0412034`].

[42] CLEO collaboration, R. Godang et al., *Search for D^0-$\bar{D}^0$ mixing*, *Phys. Rev. Lett.* **84** (2000) 5038 [`hep-ex/0001060`].

[43] BELLE collaboration, K. Abe et al., *Measurement of $D_0 - \bar{D}_0$ mixing in $D_0 \to K_s\pi^+\pi^-$ decays*, `hep-ex/0704.1000`.