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Recent charm mixing results from BABAR, Belle, and CDF

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Abstract

A summary of the results of several recent studies of charm mixing is presented. A number of different methods were used, including the measurement of lifetime ratios for final states of different CP, time dependence of wrong-sign hadronic decays, fits to time-dependent Dalitz plots, and searches for wrong-sign semi-leptonic decays. Taken together, they suggest mixing is of order 1%. The status of searches for indirect CP violation is also reported.

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1 INTRODUCTION

There has been an abundance of experimental results on charm meson mixing recently, following the watershed announcements by the *BABAR* and Belle collaborations that they had independently seen evidence for it at the level of three standard deviations (σ) [1, 2]. This paper presents a summary of new measurements from *BABAR* [3], Belle [4], and CDF [5], together with a brief discussion of the mixing formalism and implications for physics beyond the Standard Model (SM). In addition, the CLEO collaboration has produced a number of results relevant to charm mixing; these were discussed in a separate talk at this conference [6].

1.1 Mixing formalism

The charmed mesons are produced as flavour eigenstates D^0 and $\overline{D}^0$. To obtain the time evolution of these states, we express them as a linear combination of the eigenstates of the Hamiltonian, $D_{1,2}$:

$$|D_1\rangle = p\left|D^0\right\rangle + q\left|\overline{D}^0\right\rangle \quad (1)$$

$$|D_2\rangle = p\left|D^0\right\rangle - q\left|\overline{D}^0\right\rangle, \quad (2)$$

where $|q|^2 + |p|^2 = 1$ and CPT conservation is assumed. The time evolution of the states $D_{1,2}$ is simply given by the Schroedinger equation:

$$|D_{1,2}(t)\rangle = e^{-i(m_{1,2}-i\Gamma_{1,2}/2)t}\,|D_{1,2}(t=0)\rangle\,, \quad (3)$$

where $m_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths of the states $D_{1,2}$, respectively. Combining equations 1–3, we can invert the expressions above to obtain the the time-dependence of the flavour eigenstates $|D^0\rangle$ and $|\overline{D}^0\rangle$ in terms of the parameters p, q, $m_{1,2}$, and $\Gamma_{1,2}$. If $m_1 \neq m_2$ or $\Gamma_1 \neq \Gamma_2$ then mixing will occur: a state which is initially composed only of D^0 will in general contain a component of $\overline{D}^0$ at time $t > 0$, and vice versa. We quantify this effect with the dimensionless mixing parameters x and y, defined as:

$$x = \tfrac{\Delta m}{\Gamma} = \tfrac{m_1 - m_2}{\Gamma} \quad (4)$$

$$y = \tfrac{\Delta\Gamma}{2\Gamma} = \tfrac{\Gamma_1 - \Gamma_2}{2\Gamma}, \quad (5)$$

where $\Gamma = (\Gamma_1 + \Gamma_2)/2$. We also define $R_M = (x^2 + y^2)/2$.

In the SM, mixing can occur through short-range box-diagram processes, and through long-range rescattering processes via intermediate hadronic states. The former are heavily suppressed by the GIM mechanism or by $|V_{ub}V_{cb}|^2$, and are expected to be small in comparison to the long-range contributions [7]. The latter are difficult to calculate precisely, with some recent predictions for x and y of order 10^{-2} to 10^{-3} [7]. New physics (NP) beyond the SM could also contribute, but unless the effect were extremely large it would be obscured by current theoretical uncertainties in the SM mixing rate. Experimental upper limits on the mixing parameters have been used to constrain the parameter space of NP models [8].

The situation is quite different for CP violation (CPV): SM contributions to direct CPV are expected to be small ($\mathcal{O}(10^{-3})$ or less, depending on the final state), and indirect CPV should be negligible [9]. Therefore, if CPV were observed in the charm system at the present level of experimental sensitivity, it would be strong evidence for physics beyond the SM.

2 EXPERIMENTAL RESULTS

2.1 Common reconstruction and selection strategies

Charm mixing is a small effect. Therefore, each of the analyses described below relies on having a very clean sample of correctly reconstructed charm decays: significant levels of background would wash out a mixing signal and ruin the sensitivity. The main sources of background are combinatoric (e.g. tracks from light quark jets) and mis-reconstructed charm decays. Secondary charm mesons produced in B decays must either be removed or have their production vertices measured accurately.

Background is suppressed by restrictions on the kinematic properties of the D^0 candidate: the center-of-mass frame momentum, the measured proper lifetime and the associated uncertainty, and the invariant mass. Particle identification (PID) requirements are also imposed on its daughters. The D^0 candidate must also come from a reconstructed $D^{*+} \to D^0\pi^+$ or $D^{*-} \to \overline{D}{}^0\pi^-$ decay and pass corresponding kinematic selection criteria.

2.2 Decays to CP eigenstates

If mixing is present, the decay time distributions of D^0 mesons to final states with different CP may vary. This effect is familiar from the kaon system, where the mean lifetime of K^0 decaying to CP-even states is very much shorter than for CP-odd states. The charm system does not have such a dramatic difference, but with precision studies of the large *BABAR* and Belle data samples it is possible to search for percent-level effects. The results from recent searches by *BABAR* [10] and Belle [2] are presented below.

Since the level of mixing is small, the expected decay time distribution of D^0 ($\overline{D}{}^0$) to a CP-even final state h^+h^- for $h = K, \pi$ can be approximated as a single exponential with mean lifetime τ^+_{hh} (τ^-_{hh}). We also approximate the distribution for the right-sign (RS) decay $D^0 \to K^-\pi^+$ and its complex conjugate as a single exponential with mean $\tau_{K\pi} = 1/\Gamma$. We can then define the mixing parameter y_{CP} and the CP observables A_Γ and ΔY as:

$$y_{CP} = \frac{\tau_{K\pi}}{(\tau^+_{hh} + \tau^-_{hh})/2} - 1 \tag{6}$$

$$A_\Gamma = -\frac{\tau^+_{hh} - \tau^-_{hh}}{\tau^+_{hh} + \tau^-_{hh}} \tag{7}$$

$$\Delta Y = -\frac{\tau_{K\pi}}{(\tau^+_{hh} + \tau^-_{hh})/2} A_\Gamma. \tag{8}$$

In the absence of CPV, $A_\Gamma = \Delta Y = 0$ and $y_{CP} = y$. In the absence of mixing, all three parameters are zero.

Since the measured quantities are ratios of the mean lifetimes of topologically identical and kinematically similar final states, many systematic effects cancel. For example, in a study of simulated events the *BABAR* collaboration showed that misalignment of the silicon vertex detector could introduce a bias of order 3 fs (0.7%) in the measured lifetimes—but that it was almost completely correlated between the different final states and had only a small effect (0.06%) on y_{CP} and ΔY.

Both Belle and *BABAR* use strict selection criteria to suppress background, as discussed in section 2.1. *BABAR* also places a requirement on the cosine of the helicity angle of the decay. Background suppression is crucial to this analysis since the composition of the backgrounds differs

Table 1: Fit results for y_{CP} and for the CP-violating observable used (ΔY for *BABAR* and A_Γ for Belle).

Sample	y_{CP}	CPV
Belle tagged (540 fb^{-1})	$(1.31 \pm 0.32 \pm 0.25)\%$	$(+0.01 \pm 0.30 \pm 0.15)\%$
BABAR tagged (384 fb^{-1})	$(1.24 \pm 0.39 \pm 0.13)\%$	$(-0.26 \pm 0.36 \pm 0.08)\%$
BABAR untagged (91 fb^{-1})	$(0.8 \pm 0.4^{+0.5}_{-0.4})\%$	$(-0.8 \pm 0.6 \pm 0.2)\%$

between final states, and so the systematic uncertainties associated with modelling the rate and time-dependence of background typically do not cancel when taking ratios of lifetimes.

The results of the fit are shown in Table 1. Both collaborations find evidence for mixing (with statistical significance of 3.0σ and 3.2σ for *BABAR* and Belle, respectively); neither finds evidence for CPV. In addition, an older result from *BABAR* is shown [11]: the data sample used contained only D^0 not tagged with a D^* decay and is statistically independent from the more recent analysis of tagged mesons.

2.3 Wrong-sign hadronic decays

The time-dependence of the decay rate to other final states is also affected by mixing. The effect is clearest for wrong-sign (WS) decays such as $D^0 \to K^+\pi^-$, which in the absence of mixing occur only via doubly-Cabibbo-suppressed (DCS) decays with a small rate R_D and have a pure exponential distribution of the form $\Gamma_{WS}(t) \propto R_D e^{-\Gamma t}$. When mixing is allowed, a second mechanism opens up: an initially pure D^0 state will evolve to include a component of $\overline{D}^0$ that can undergo a Cabibbo-favoured (CF) decay to $K^+\pi^-$. Assuming that the mixing rate is small and neglecting CP violation, the time-dependence then becomes

$$\frac{\Gamma_{WS}(t)}{e^{-\Gamma t}} \propto R_D + y'\sqrt{R_D}(\Gamma t) + \frac{x'^2 + y'^2}{4}(\Gamma t)^2 \tag{9}$$

where $x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$, $y' = -x\sin\delta_{K\pi} + y\cos\delta_{K\pi}$, and $\delta_{K\pi}$ is the strong phase between the DCS and CF amplitudes. By fitting this time-dependence, the mixing parameters x'^2 and y' can be extracted. When allowing for CPV, the form of Eq. 9 remains the same but has separate coefficients $R_D^\pm$, $x'^{2\pm}$, and $y'^\pm$ for D^0 decays (+) and $\overline{D}^0$ decays (−).

BABAR, Belle, and CDF have carried out searches for mixing in WS $D^0 \to K^+\pi^-$ events in samples of 384, 400, and 1.5 fb^{-1} of data, respectively [1, 12, 13], using the selection criteria described in section 2.1. The mixing parameters obtained are shown in Table 2. *BABAR* and CDF find mixing signals with statistical significances of 3.9σ and 3.8σ respectively, indicating clear evidence for mixing. *BABAR* and Belle also searched for CPV, but found no evidence for such an effect.

The mixing parameters of other WS hadronic decays can be extracted from their time-dependence in a similar fashion. With multi-body decays such as $D^0 \to K^+\pi^-\pi^0$, additional sensitivity can be gained by including the position of each event within the Dalitz plot in the fit, since the distributions of the DCS and CF decays differ. *BABAR* has used this technique in a search for mixing in $D^0 \to K^+\pi^-\pi^0$, obtaining a preliminary result of $R_M = (2.9 \pm 1.6) \times 10^{-4}$ from a sample of 384 fb^{-1}.

Table 2: Results from fits to WS $D^0 \to K^+\pi^-$ decays. The DCS rate R_D and mixing parameters y' and x'^2 are given, along with the statistical significance of the mixing signal in standard deviations. Where measured, the CP-violating asymmetry parameters A_D and A_M are given; these are the asymmetries in R_D and R_M, respectively.

Experiment	$R_D(10^{-3})$	y'	x'^2	Signif.	A_D (%)	A_M
CDF (1.5 fb^{-1})	3.04 ± 0.55	8.5 ± 7.6	-0.12 ± 0.35	3.8		
BABAR (384 fb^{-1})	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37	3.9	$-2.1 \pm 5.2 \pm 1.5$	
Belle (400 fb^{-1})	3.64 ± 0.17	$0.6^{+4.0}_{-3.9}$	$0.18^{+0.21}_{-0.23}$	2.0	2.3 ± 4.7	0.62 ± 1.2

2.4 $D^0 \to K_S\pi^+\pi^-$

As a special case of the analyses discussed above, final states such as $K_S\pi^+\pi^-$ contain several different classes of contribution in the same Dalitz plot. These include RS decays (e.g. $D^0 \to K^{*-}\pi^+$), WS decays (e.g. $D^0 \to K^{*+}\pi^-$), CP-even final states (e.g. $K_S\rho^0$), and CP-odd final states (e.g. $K_S f_0$). All of these amplitudes are present in the same Dalitz plot and interfere, allowing their relative phases to be determined in the fit. As a result, the mixing parameters x and y can be measured directly. The Belle collaboration has carried out a search for mixing in this final state in 540 fb^{-1} of data [14] and obtained:

$$x = \left(0.80 \pm 0.29\,{}^{+0.09}_{-0.07}\,{}^{+0.10}_{-0.14}\right)\%$$
$$y = \left(0.33 \pm 0.24\,{}^{+0.08}_{-0.12}\,{}^{+0.06}_{-0.08}\right)\%.$$

They found no evidence for CP violation.

2.5 Semi-leptonic decays

In contrast to the hadronic processes discussed above, for which there are multiple contributions to the same final state including a non-mixing component, wrong-sign semi-leptonic decays $D^0 \to K^{(*)+}l^-\bar{\nu}_l$ can only occur via mixing in the Standard Model—and so any observation would be unambiguous evidence of mixing. However, the experimental reconstruction and selection of these events is made more difficult because the reconstructed D^0 is incomplete—the neutrino and possibly additional K^{*+} daughters are not found—and so the power of the kinematic selection criteria discussed in section 2.1 is reduced.

BABAR and Belle both search for mixing in these final states, but use quite different techniques. *BABAR* uses only $l = e$ and obtains a very pure sample with a double-tag technique: in addition to the signal-side D^0, the recoiling charm decay in the opposite hemisphere of the event is also reconstructed. This lowers the background dramatically, but also reduces the signal efficiency. They find no evidence for mixing in a sample of 344 fb^{-1} [15] and set a 90% confidence interval of $-13 \times 10^{-4} < R_M < 12 \times 10^{-4}$. This is entirely consistent with the evidence for mixing discussed above, which found $R_M \sim 10^{-4}$.

Belle use both the electron and muon decay modes and do not require an opposite-side tag. Instead they apply additional kinematic constraints to the K^+l^- system, and use information on the missing energy and momentum in the event to improve the reconstruction and allow more stringent selection criteria. They find no evidence for mixing in a sample of 492 fb^{-1} and set a preliminary 90% confidence limit of $R_M < 6.1 \times 10^{-4}$ [16].

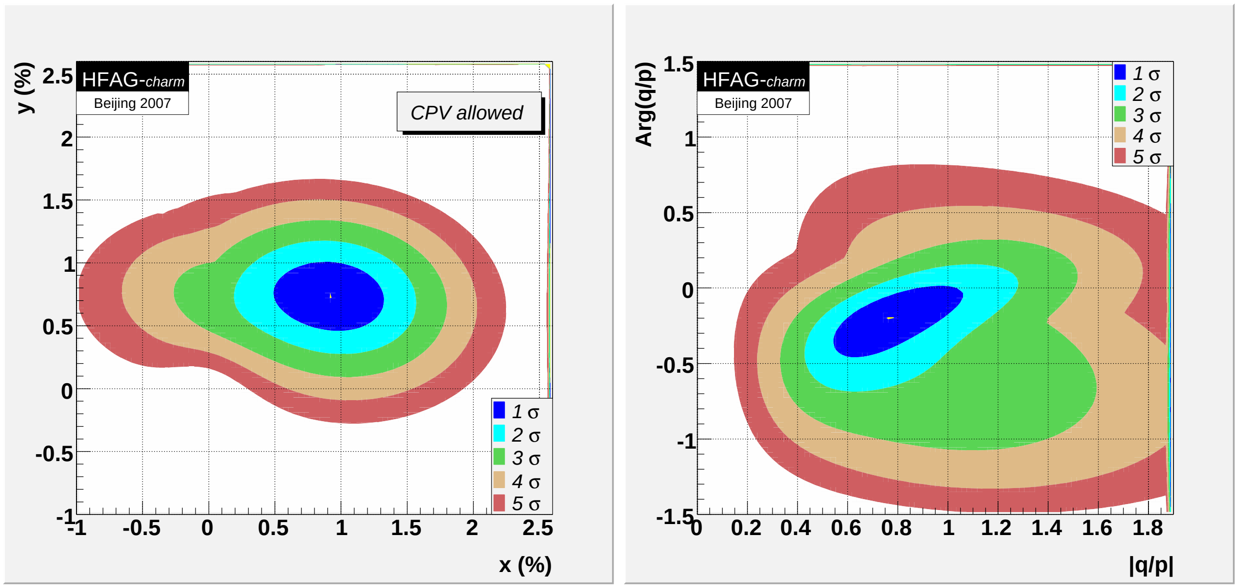

Figure 1: World-average results from the HFAG. The left plot shows limits on the mixing parameters x and y allowing for CPV, and the right plot shows the limits on the CPV parameters $\arg(q/p)$ and $|q/p|$.

2.6 Combined results

By combining the above results with other relevant measurements, the Heavy Flavor Averaging Group (HFAG) has determined world-average values and confidence intervals for the mixing and CPV parameters [17]. These are illustrated in Fig. 1. Allowing CPV, they find:

$$
\begin{aligned}
x &= \left(0.97^{+0.27}_{-0.29}\right)\% \\
y &= \left(0.78^{+0.18}_{-0.19}\right)\% \\
|q/p| &= 0.86^{+0.18}_{-0.15} \\
\arg(q/p) &= \left(-0.17^{+0.14}_{-0.16}\right)\ \text{rad.}
\end{aligned}
$$

The zero-mixing hypothesis ($x = y = 0$) is excluded at the level of 6.7σ, but the data are still consistent with zero indirect CPV ($|q/p| = 1$, $\arg(q/p) = 0$ is on the 1σ contour).

3 CONCLUSIONS

Charm mixing is now established, with a combined world significance of 6.7σ. However, no single measurement has yet exceeded five standard deviations and there are large uncertainties on the mixing parameters—there is still more work to do, and we are still statistically limited. The observed mixing rate is consistent with the SM predictions, albeit within large theory and experimental uncertainties, and appears to be at the upper end of the expected range. There has been no sign of CP violation, direct or indirect, in the charm system yet. However, limits on CPV are still well above the SM expectations and there is plenty of room for new physics to emerge in future measurements.

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