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Charm Mixing and *CP* Violation at *BABAR*

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We report on the latest searches for $D^0 - \bar{D}^0$ mixing and *CP* violation in charm decays at the *BABAR* experiment. We present a measurement of the lifetime ratio parameter y_{CP} in the two-body K^-K^+ and $\pi^-\pi^+$ final states that excludes the no mixing hypothesis with a significance of 3.3σ. A search for indirect *CP* violation in the same channels has also been performed. A search for *CPV* in the $D^+ \to K_S^0 K^+$, $D_s^+ \to K_S^0 K^+$, $D_s^+ \to K_S^0 \pi^+$ and $D^+ \to K^+K^-\pi^+$ decays is also presented. No indication of *CPV* in charm decays is found.

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1. Introduction

The study of mixing and *CP* violation in the charm sector represents a test of the up-type quark sector for the Standard Model (SM). It therefore brings a complementary information with respect to the other mixing systems, and it also allows to probe and put constraints in the space of parameters of theories beyond the SM.

Mixing in the charm sector has been confirmed by several measurements in the past few years, all in agreement with the SM predictions. The first observation of $D^0-\bar{D}^0$ mixing with a significance of $\sim 9\sigma$ was reported in November 2012 [1] by the LHCb Collaboration. Around 3.6×10^4 of $D^0\to K^+\pi^-$ decays and 8.4×10^8 of $D^0\to K^-\pi^+$ decays were analyzed, and the time-dependent ratio between the two decay modes was determined to be varying in time, as expected in case of mixing. On the other hand, the interpretation of the evidence of *CP* violation (*CPV*) in the difference of integrated asymmetries between $D^0\to K^-K^+$ and $D^0\to\pi^-\pi^+$ decays reported by LHCb [2] and CDF [3] is still open. The measured asymmetry is marginally compatible with the SM predictions that are affected by important uncertainties that limit its intrinsic power in probing the SM. No indication of *CPV* in charm has been found in other decays.

2. Searches for Direct *CP* Violation

Direct *CP* violation is the only source of *CPV* in charged meson decays. It occurs when the magnitude of the decay amplitude of the process $D\to f$ (A_f) differs from the amplitude of the *CP*-conjugate process $\bar{D}\to\bar{f}$ ($\bar{A}_{\bar{f}}$), $\left|A_f/\bar{A}_{\bar{f}}\right|\neq 1$. This is possible only if there are two contributions to the single amplitude with different weak and strong phases. The experimental observable is the time-integrated asymmetry defined as:

$$A^f_{CP}=\frac{\Gamma(D\to f)-\Gamma(\bar{D}\to\bar{f})}{\Gamma(D\to f)+\Gamma(\bar{D}\to\bar{f})}. \tag{2.1}$$

The *CP* asymmetry differs from the directly experimentally accessible raw asymmetry (in D and $\bar{D}$ yields). The forward-backward asymmetry ($A_{\rm FB}$) in the $c\bar{c}$ production coupled with the non-hermiticity of the detector contributes to the raw asymmetry, as well as the detector-induced charge-reconstruction asymmetry (A_ε). The first contribution can be decoupled from A_{CP} exploiting the fact that $A_{\rm FB}$ has an odd dependence on the polar angle of the D in the center of mass (θ^*), while A_{CP} does not depend on that angle. The measurement is performed in bins of $\cos\theta^*$ and then the raw asymmetries in symmetric bins are combined to extract A_{CP}. The contribution of A_ε can be removed with data-driven techniques that exploit a high-statistics control sample free on any physical *CP* violation: the signal events are weighted with appropriate factors estimated from the independent control sample and depending on the momentum of the tagging charged track. Finally, if a K^0_S is present in the final state, the contribution of *CPV* from the $K^0-\bar{K}^0$ system needs to be disentangled from the charm contribution. The Standard Model predicts this contribution to be $(+(-)0.332\pm0.0006)\%$ in case a K^0 ($\bar{K}^0$) is present in the final state.

2.1 $D^+\to K^0_SK^+$, $D^+_s\to K^0_SK^+$ and $D^+_s\to K^0_S\pi^+$ decay channels

The method to extract the *CP* asymmetry for these channels is essentially the same used in the already published $D^+\to K^0_S\pi^+$ analysis [4]. We reconstruct a total of $(154.4\pm0.8)\times10^3$

signal events in the $D^+ \to K_S^0 K^+$ [5] channel, $(288.2 \pm 1.1) \times 10^3$ signal events in the $D_s^+ \to K_S^0 K^+$ channel and $(14.3 \pm 0.3) \times 10^3$ signal events in the $D_s^+ \to K_S^0 \pi^+$ channel. The detector-induced charge-reconstruction asymmetry is removed weighting the reconstructed events with the ratio of efficiencies evaluated with a high-statistics $e^+e^- \to B\overline{B}$ control sample. The correction is applied in bins of the momentum of the tagging charged tracks. We perform a simultaneous maximum likelihood (ML) fit to the mass distribution in ten bins of $\cos\theta^*$ for each channel and combine symmetric bins to extract five values of A_{CP}. The value of the asymmetry is extracted with a χ^2 fit with a constant to the five values. The values of A_{CP} from the fit can be found in the first row of Table 1. These values are corrected by small biases related to the effects of $K_S^0 - K_L^0$ interference and the particle identification selectors. We correct also for a small bias found in Toy MC studies. The final value of *CPV* in charm is obtained removing the contribution from $K^0 - \bar{K}^0$ mixing and it is reported in the last row of Table 1. The main systematic errors are statistically limited. The largest contribution in the $D_s^+ \to K_S^0 \pi^+$ channel is related to the binning in $\cos\theta^*$, while for the channels with the tagging K, the main systematic is related to the limited statistics of the control sample used to correct the detector-induced charge-reconstruction asymmetry.

Table 1: Summary table of A_{CP} measurements in two-body final states. The first reported uncertainty is statistical, the second systematic (BABAR preliminary).

	$D^+ \to K_S^0 K^+$	$D_s^+ \to K_S^0 K^+$	$D_s^+ \to K_S^0 \pi^+$
A_{CP} value from the fit	$(0.16 \pm 0.36)\%$	$(0.00 \pm 0.23)\%$	$(0.6 \pm 2.0)\%$
Bias Corrections			
Toy MC experiments	$+0.0013\%$	-0.01%	–
PID selectors	-0.05%	-0.05%	-0.05%
$K_S^0 - K_L^0$ interference	$+0.015\%$	$+0.014\%$	-0.008%
A_{CP} corrected value	$(0.13 \pm 0.36 \pm 0.25)\%$	$(-0.05 \pm 0.23 \pm 0.24)\%$	$(0.6 \pm 2.0 \pm 0.3)\%$
A_{CP} contribution from $K^0 - \bar{K}^0$ mixing	$(-0.332 \pm 0.006)\%$	$(-0.332 \pm 0.006)\%$	$(+0.332 \pm 0.006)\%$
A_{CP} value (charm only)	$(0.46 \pm 0.36 \pm 0.25)\%$	$(0.28 \pm 0.23 \pm 0.24)\%$	$(0.3 \pm 2.0 \pm 0.3)\%$

2.2 $D^+ \to K^+K^-\pi^+$ decay channel

With a three-body final state additional sensitivity to *CPV* can be achieved studying the distribution of the events on the Dalitz plot (DP). Therefore, beside the measurement of A_{CP} similar to the one described in the previous section, alternative methods have been used to search for enhanced *CPV* effects in certain regions of the DP.

The data sample consists of $(228.0 \pm 0.8) \times 10^3$ signal events, representing 92% of the selected events. The detector-induced charge-reconstruction asymmetry has been corrected using a $e^+e^- \to \tau^+\tau^-$ data control sample in bins of the DP and of $\cos\theta^*$. The DP integrated measurement of A_{CP} is performed with the same procedure as the above described analysis, except that in this case data is divided in 8 bins of $\cos\theta^*$. The obtained final value is $A_{CP} = (0.35 \pm 0.30 \pm 0.15)\%$, compatible with no *CPV*. Since no effect of *CPV* has been found integrating over the DP, the ratio of efficiency-corrected signal yields, $R = \frac{N(D^+)/\varepsilon(D^+)}{N(D^-)/\varepsilon(D^-)} = 1.020 \pm 0.006$ has been then used to correct for the forward-backward asymmetry in the Dalitz-dependent approaches described in the following.

The first model-independent search for *CPV* in the DP is similar to the previous one: the DP has been divided in four regions and the *CP* asymmetry has been evaluated in each of these regions, fitting the mass distributions of D^+ and D^- decays. The results are reported in Table 2, no evidence of *CPV* has been found.

Table 2: Summary table of A_{CP} measurement in DP regions for the $K^+K^-\pi^+$ final state. The first reported uncertainty is statistical, the second systematic (BABAR preliminary).

Dalitz Plot Region	$N(D^+)$	$\varepsilon(D^+)[\%]$	$N(D^-)$	$\varepsilon(D^-)[\%]$	$A_{CP}[\%]$
Below $K^*(892)^0$	1882 ± 70	7.00	1859 ± 90	6.97	$-0.65 \pm 1.64 \pm 1.73$
$K^*(892)^0$	36770 ± 251	7.53	36262 ± 257	7.53	$-0.28 \pm 0.37 \pm 0.21$
$\phi(1020)$	48856 ± 289	8.57	48009 ± 289	8.54	$-0.26 \pm 0.32 \pm 0.45$
Above $K^*(892)^0$ and $\phi(1020)$	25616 ± 244	8.01	24560 ± 242	8.00	$+1.45 \pm 0.45 \pm 0.31$

Two additional DP model-independent approaches has also been used but none of them showed evidence of *CPV*. In the first approach, the DP has been divided in equally-populated bins and the distribution of the normalized residuals of efficiency-corrected and background subtracted yields ($n(D^{\pm})$),

$$\Delta = \frac{n(D^+) - n(D^-)}{\sqrt{\sigma^2(D^+) + R^2\sigma^2(D^-)}}, \tag{2.2}$$

has been fit with a Gaussian finding the mean compatible with zero and the width compatible with one within one standard deviation. These results are consistent with no *CPV* at the 72% level. The second approach is an analysis of the Legendre moments [6] of the D^+ and D^- Dalitz Plots, and again no evidence of *CPV* has been found.

Finally, a model-dependent approach based on the isobar model but allowing for different amplitudes and phases for D^+ and D^- decays into the same resonance has been carried on. The $K^*(892)^0$ has been chosen as the reference amplitude and, assuming no *CPV*, the relative fractions of resonances and a constant non-resonant amplitude have been determined with an unbinned ML fit. Then, the resonances contributing with more than 1% have been allowed to have different magnitudes and phases for D^+ and D^- decays and the parameters have been extracted with a simultaneous fit. All *CPV* parameters are consistent with zero.

3. Search for Mixing and Indirect *CP* Violation

$D^0 - \bar{D}^0$ mixing has been recently observed with almost 10 standard deviations by the LHCb Collaboration [1], exploiting the largest sample of charm decays ever collected. The two parameters that describe the time-evolution of the flavor eigenstates D^0 and $\bar{D}^0$ are proportional to the difference of masses ($m_{1,2}$) and widths ($\Gamma_{1,2}$) of the mass eigenstates:

$$x = \frac{m_1 - m_2}{\Gamma} \qquad \text{and} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \tag{3.1}$$

where Γ is the average width $\Gamma = (\Gamma_1 + \Gamma_2)/2$. If mixing occurs, then the average of the D^0 and $\bar{D}^0$ effective lifetimes when the meson is reconstructed in *CP*-even eigenstates (τ^+ and $\bar{\tau}^+$, respectively) differs with the inverse of Γ, and the parameter y_{CP}, defined below, is different from zero:

$$y_{CP} = \frac{1}{2\Gamma}\left[\frac{1}{\tau^+} + \frac{1}{\bar{\tau}^+}\right] - 1. \tag{3.2}$$

The difference between the D^0 to the $\bar{D}^0$ effective lifetimes, τ^+ and $\bar{\tau}^+$, is sensitive to *CP* violation. If the parameter ΔY, defined below, differs from zero, then *CPV* occurred,

$$\Delta Y = \frac{1}{2\Gamma}\left[\frac{1}{\tau^+} - \frac{1}{\bar{\tau}^+}\right]. \tag{3.3}$$

Effects of *CPV* in D^0 decays may include also *CP* violation in mixing and in the interference between decays with and without mixing. In this analysis we neglect the effects of direct *CPV*, estimated to be one order of magnitude below the experimental sensitivity. In case of no mixing, both parameters are expected to be zero, and in case of no *CPV* $y_{CP} = y$ and ΔY = 0.

We analyze 468 fb^{-1} of $\Upsilon(4S)$ decays reconstructing the D^0 in three D^{*+}-tagged decays ($D^{*+} \to D^0\pi^+$): $D^0 \to \pi^+\pi^-$, $D^0 \to K^+K^-$, $D^0 \to K^\mp\pi^\pm$ and two untagged decays: $D^0 \to K^+K^-$ and $D^0 \to K^\mp\pi^\pm$. The tagged and untagged samples are independent. The D^0 ($\bar{D}^0$) decays to K^-K^+ and $\pi^-\pi^+$ final states are described with the effective lifetime τ^+ ($\bar{\tau}^+$), while D^0 and $\bar{D}^0$ decays to $K^\mp\pi^\pm$ are described with the lifetime parameter $\tau_{K\pi}$, assumed to be proportional to the inverse of Γ. The three lifetime parameters are extracted with a simultaneous extended unbinned ML fit to the events in the signal region, where the background contributions are fixed.

The first step of the analysis consists of a fit to the mass distributions of the five channels in order to extract the total background yields. The background events are classified in two categories. The charm background consists in mis-reconstructed charm decays, it represents a tiny fraction of the events in the signal region ($\leq 0.7\%$) but it has a long lifetime and needs to be separated from the combinatorial background events, a prompt background. The shape and yields of the charm background are extracted from the simulated events. The combinatorial shape is extracted from the mass sidebands, as a weighted average of the PDFs in the two sidebands, while the yields is computed using the mass fits results. The startging value of combinatorial yields for the untagged K^-K^+ channel is estimated from the mass fit but then it is left floating in the final fit.

Before analyzing the results of the fit we evaluate the systematic errors on both observables. The most important systematic error on y_{CP} is related to the extraction of the combinatorial PDFs from the mass sidebands. The most important error on ΔY is the impact of the selection criteria imposed on the proper time error, this is one of the largest error on y_{CP} also. The third important contribution is related to the choice of the signal region width, as consequence of the observed correlation between the reconstructed mass and proper time. Other sources of systematic errors are the shape and yields of the two background categories. The impact of the detector misalignment has been evaluated to be negligible.

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The effective lifetimes extracted from the simultaneous fit are $\tau^+ = (405.69 \pm 1.25)$ fs, $\overline{\tau}^+ = (406.40 \pm 1.25)$ fs and $\tau_{K\pi} = (408.97 \pm 0.24)$ fs, where the error is statistical only. Combining the three lifetimes and using the covariance matrix from the fit, we obtain the following values for the mixing and *CPV* parameters:

$$y_{CP} = (0.72 \pm 0.18 \pm 0.12)\% \qquad \text{and} \qquad \Delta Y = (0.09 \pm 0.26 \pm 0.06)\%, \tag{3.4}$$

where the first error is statistical and the second systematic. We find no evidence of *CPV*. The no mixing hypothesis is excluded with a significance of 3.3σ. The reported measurement of y_{CP} is the most precise single measurement of the parameter, it is compatible with the previous *BABAR* measurement [7] and it supersedes it.

4. Conclusions and Acknowledgments

In conclusion, we have reported on the searches for direct and indirect *CPV* in charm decays with the full *BABAR* data sample. No evidence of *CPV* has been found. We also reported a 3.3σ significant measurement of mixing with the lifetime-ratio parameter y_{CP}.

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