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Searches for *CP* violation in charm decays at *BABAR*

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Abstract

In the Standard Model *CP* violation in charm decays is expected to be very small, at the level of 0.1% or less. A significant excess of *CP* violation with respect to the Standard Model predictions would be a signature of new physics. We report on recent searches for *CP* violation in charm meson decays at *BABAR*, using a data sample corresponding to an integrated luminosity of about 470 fb^{-1}. In particular, we report on searches for *CPV* in the 3-body $D^+ \to K^+K^-\pi^+$ decay and for decay modes with a K_S^0 in the final state, such as $D^+ \to K_S^0 K^+$, $D_s^+ \to K_S^0 K^+$, $D_s^+ \to K_S^0 \pi^+$. A lifetime ratio analysis of $D^0 \to K^+K^-, \pi^+\pi^-$ with respect to $D^0 \to K^-\pi^+$ decays, which is sensitive to D^0-$\overline{D}^0$ mixing and *CP* violation, is also presented here.

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1 Introduction

In the Standard Model (SM) *CP* violation (*CPV*) is accommodated by the CKM [1, 2] mechanism which regulates the mixing of the three families of quarks. This mechanism has been proved to work well according to the experimental results that have been provided mostly by the *B*-Factory experiments, *BABAR* and Belle, during the last decade. However, the CKM mechanism is not sufficient to describe the absence of antimatter in the universe, and so this represents an open question for both experimental and theoretical physicists. Other sources of *CPV* are currently under investigation, and the charm sector represents an interesting probe for this purpose.

In charm meson decays *CPV* is expected to be at the level of 0.1% or less [3, 4], although the predictions are affected by large theoretical uncertainties due to long distance interactions. The study of *CPV* in singly Cabibbo-suppressed (SCS) charm decays is particularly sensitive to new physics (NP) [4], while evidence of indirect *CPV* in D^0-$\overline{D}^0$ mixing, with the current experimental precision, would be a clear sign for NP. Throughout the following discussion the use of charge conjugate reactions is implied, unless otherwise indicated.

2 Search for direct *CPV* in $D^+ \to K^+K^-\pi^+$ decay

The *BABAR* experiment has recently searched for *CPV* in the singly Cabibbo-suppressed $D^+ \to K^+K^-\pi^+$ decay using a data sample corresponding to an integrated luminosity of 476 fb^{-1} [5]. The 3-body decay proceeds mainly through quasi-two-body decays with resonant intermediate states, which allows the investigation of the Dalitz plot substructure for asymmetry in both magnitude and phase for each intermediate state. In the search for *CPV*, 5 different approaches were adopted: a measurement of the integrated *CP* asymmetry, a measurement of the *CP* asymmetry in four regions of the Dalitz plot, a comparison of the binned D^+ and D^- Dalitz plots, a comparison of the Legendre-polynomial-moment weighted distributions in the K^+K^- and $K^-\pi^+$ systems, and a comparison of the results of a parameterized fit to the D^+ and D^- Dalitz plots. Only the last one is model-dependent, while the previous four approaches are model-independent.

The signal yield is about 223,700 events, with signal purity of about 92%. The *CP*-violating decay rate asymmetry, A_{CP}, was determined to be $(0.37 \pm 0.30(\text{stat}) \pm 0.15(\text{syst}))\%$. The *CP* asymmetries in different regions of the Dalitz plot, defined by the reconstructed invariant mass squared values $m^2(K^-K^+)$ and $m^2(K^-\pi^+)$, are reported in Table 1. Model-independent techniques were used to search for *CPV* in the Dalitz plot. These were based on a comparison of the binned D^+ and D^- Dalitz plots, and on a comparison of the Legendre-polynomial-moment weighted distributions in the K^+K^- and $K^-\pi^+$ systems. The distributions of normalized residuals in equally

Dalitz plot region	A_{CP} (%)
Below $\overline{K}^*(892)^0$ (A)	$-0.7 \pm 1.6(\text{stat}) \pm 1.7(\text{syst})$
$\overline{K}^*(892)^0$ (B)	$-0.3 \pm 0.4(\text{stat}) \pm 0.2(\text{syst})$
$\phi(1020)$ (C)	$-0.3 \pm 0.3(\text{stat}) \pm 0.5(\text{syst})$
Above $\overline{K}^*(892)^0$ and $\phi(1020)$ (D)	$1.1 \pm 0.5(\text{stat}) \pm 0.3(\text{syst})$

Table 1: *CP* asymmetry in the regions (A), (B), (C) and (D) of the Dalitz plot shown in Fig. 1. The first error is statistical and the second is systematic.

populated bins ($\sim$ 1000 events per bin) of the D^+ and D^- Dalitz plots were fitted with a Gaussian function. The fit yielded a mean of 0.08 ± 0.15 and a r.m.s. deviation of 1.11 ± 0.15, which corresponds to a probability of 72% that the two Dalitz plots are consistent with no *CPV*. The comparison of Legendre-polynomial-moments for the K^+K^- and $K^-\pi^+$ systems separately was found to be consistent with no *CPV* with a probability of 11% and 13%, respectively.

A model-dependent technique based on a comparison of parameterized fits to the two Dalitz plots was also used to search for *CPV*. The D^+ decay amplitude was parameterized as a coherent sum of amplitudes describing the relevant two-body intermediate states (16 resonances) plus a constant amplitude over the Dalitz plot for the non-resonant (NR) contribution. The resonances that contribute to the fit with the largest fit fractions are the $\phi(1020)$ (28.42 ± 0.13)%, $\overline{K}^*(1430)^0$ (25.32 ± 2.24)%, and the $\overline{K}^*(892)^0$ (21.15 ± 0.20)%. The results of the fit to the D^+ and D^- Dalitz plots do not show evidence of *CPV* for the following amplitudes: $\overline{K}^*(892)^0K^+$, $\overline{K}^*(1430)^0K^+$, $\phi(1020)\pi^+$, NR, $\overline{\kappa}(800)^0K^+$, $a_0(1450)^0\pi^+$, $f_0(980)\pi^+$, $f_0(1370)\pi^+$.

3 Search for *CPV* in $D^+ \to K^0_S K^+$ and $D^+_s \to K^0_S K^+, K^0_S \pi^+$ decays

In D meson decays with a K^0_S in the final state, *CP*-violating asymmetries defined as

$$A_{CP} = \frac{\Gamma(D^+_{(s)} \to K^0_S h^+) - \Gamma(D^-_{(s)} \to K^0_S h^-)}{\Gamma(D^+_{(s)} \to K^0_S h^+) + \Gamma(D^-_{(s)} \to K^0_S h^-)} = A^{\Delta C}_{CP} + A^{K^0_S}_{CP}, \quad (1)$$

can receive contributions from *CPV* in $\Delta C = 1$ quark transitions ($A^{\Delta C}_{CP}$), and from *CPV* in K^0-$\overline{K}^0$ mixing ($A^{K^0_S}_{CP}$). The value of the contribution from K^0-$\overline{K}^0$ mixing is precisely determined to be $A^{K^0_S}_{CP} = [\pm 0.332 \pm 0.006]$% [6], where the $\pm$ sign depends on whether a K^0 (+) or a $\overline{K}^0$ (-) is produced in the decay. The SM prediction has to be corrected for the detector acceptance as a function of the decay time [7], and the correction is at the level of few percent at the B factories. A sizable deviation

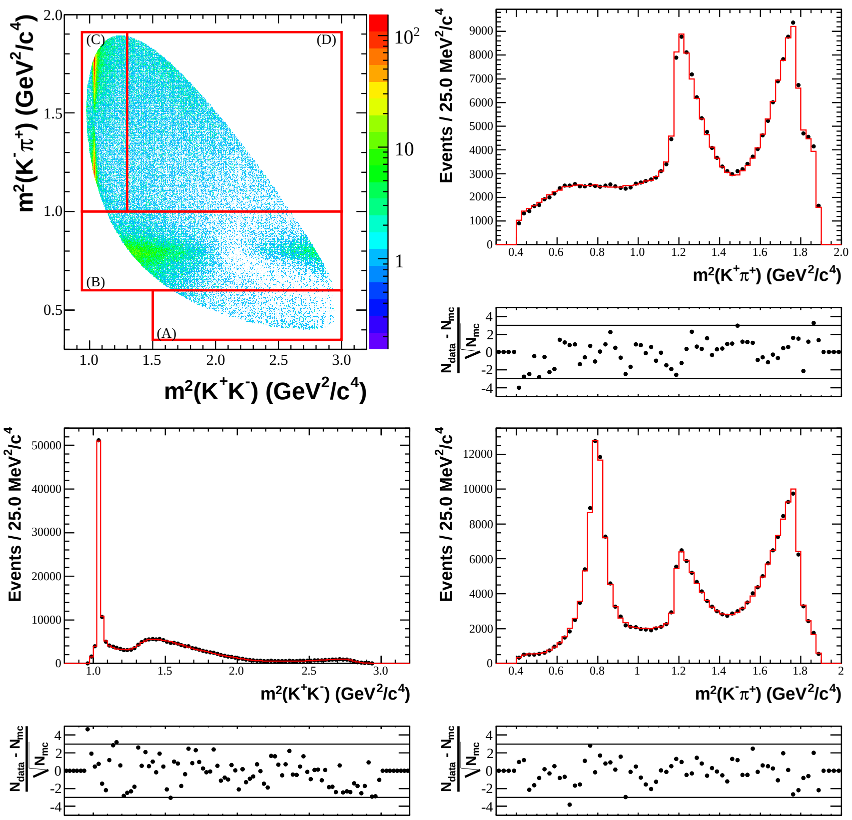

Figure 1: $D^+ \to K^+K^-\pi^+$ Dalitz plot and fit projections assuming no CPV, with the regions used for model-independent comparisons also indicated as boxes. For each projection, the data are represented by points with errors, and the fit result by the histogram. The normalized residuals below each histogram, defined as $(N_{Data} - N_{MC})/\sqrt{N_{MC}}$, lie between $\pm 5\sigma$.

of the measured A_{CP} value from the $A_{CP}^{K_S^0}$ predicted value would indicate CPV in the $\Delta C = 1$ quark transition, and might indicate NP effects.

The *BABAR* experiment has recently searched for CP asymmetries in the $D^+_{(s)} \to K_S^0 K^+$ and $D_s^+ \to K_S^0\pi^+$ decay modes [8] using a data sample corresponding to an integrated luminosity of 469 fb^{-1}. The reconstructed asymmetry is defined as

$$A_{rec} = \frac{N_{D^+_{(s)}} - N_{D^-_{(s)}}}{N_{D^+_{(s)}} + N_{D^-_{(s)}}} = A_{CP} + A_{FB} + A_{\epsilon}, \quad (2)$$

where $N_{D^+_{(s)}}$ ($N_{D^-_{(s)}}$) is the number of $D^+_{(s)}$ ($D^-_{(s)}$) decays determined from the fit to the relevant invariant mass distribution, A_{FB} is the forward-backward (FB) asymmetry, and A_ϵ is the detector-induced charge reconstruction asymmetry; A_{FB} originates from the FB asymmetry in $e^+e^- \to c\bar{c}$ production, coupled with the asymmetric acceptance of the detector, and is measured directly on data together with A_{CP} [9]. The fits to the $m(K_S^0 h)$ distributions yield $(159.4 \pm 0.8) \times 10^3$ signal events for $D^+ \to K_S^0 K^+$, $(288.2 \pm 1.1) \times 10^3$ for $D_s^+ \to K_S^0 K^+$, and $(14.33 \pm 0.31) \times 10^3$ for $D_s^+ \to K_S^0 \pi^+$.

The *CP*-violating asymmetries A_{CP} for the $D^+ \to K_S^0 K^+$, $D_s^+ \to K_S^0 K^+$, and $D_s^+ \to K_S^0 \pi^+$ decays are determined to be $[0.13 \pm 0.36(\text{stat}) \pm 0.25(\text{syst})]\%$, $[-0.05 \pm 0.23(\text{stat}) \pm 0.24(\text{syst})]\%$, and $[0.6 \pm 2.0(\text{stat}) \pm 0.3(\text{syst})]\%$, respectively. The primary source of systematic error is due to the statistical uncertainty in the determination of the charge asymmetry in track reconstruction efficiency.

The contribution to the *CP* asymmetries due to the $\Delta C = 1$ transition is measured to be $[0.46 \pm 0.36(\text{stat}) \pm 0.25(\text{syst})]\%$, $[0.28 \pm 0.23(\text{stat}) \pm 0.24(\text{syst})]\%$, and $[0.3 \pm 2.0(\text{stat}) \pm 0.3(\text{syst})]\%$ for the respective decay processes. The results are consistent with zero, and with the SM predictions within one standard deviation.

4 Measurement of D^0-$\overline{D}^0$ mixing, and search for indirect *CPV* in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

The *BABAR* experiment has recently updated the measurement of the mixing parameter y_{CP} and the *CP*-violation parameter ΔY [10]. The definitions of ΔY^* and A_Γ are the following:

$$\Delta Y = \frac{\Gamma^+ - \overline{\Gamma}^+}{2\Gamma} = (1 + y_{CP}) A_\Gamma, \qquad A_\Gamma = \frac{\overline{\tau}^+ - \tau^+}{\overline{\tau}^+ + \tau^+}, \tag{3}$$

where $\tau^+ = 1/\Gamma^+$ ($\overline{\tau}^+ = 1/\overline{\Gamma}^+$) are the effective lifetimes for D^0 ($\overline{D}^0$) decaying to the *CP*-even final states K^+K^- and $\pi^+\pi^-$. In this analysis *CP* conservation in the decay is assumed, and results are averaged over the K^+K^- and $\pi^+\pi^-$ modes.

The measurements are based on the ratio of lifetimes extracted simultaneously from a sample of D^0 mesons produced through the flavor-tagging process $D^{*+} \to D^0\pi^+$, where the D^0 decays to $K^-\pi^+$, K^-K^+, or $\pi^-\pi^+$; additional samples of untagged decays for $D^0 \to K^-\pi^+$ and $D^0 \to K^-K^+$ are used for the measurement of y_{CP}. The latter have about 4 times the statistics of the corresponding flavor-tagged samples, but have lower purity. The flight length is reconstructed by means of a simultaneous kinematic fit to the decay vertex and production vertex of the D^0, the latter being constrained to originate within the e^+e^- collision region.

*Note that this definition for ΔY uses a different sign convention than that used in previous *BABAR* publications [11, 12].

The most probable σ_t value is about 40% of the nominal D^0 lifetime, and only candidates with $\sigma_t < 0.5\,\mathrm{ps}$ are retained for the fit. The *BABAR* experiment measures $y_{CP} = [0.72 \pm 0.18(\mathrm{stat}) \pm 0.12(\mathrm{syst})]\%$ and $\Delta Y = [0.09 \pm 0.26(\mathrm{stat}) \pm 0.06(\mathrm{syst})]\%$ using a data sample corresponding to an integrated luminosity of $468\,\mathrm{fb}^{-1}$ [10]. The measurement of y_{CP} is the most precise single measurement to date.

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