SLAC-PUB-14331

CP Violation and Mixing in Charm Meson Decays from *BABAR*

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Received Day Month Year
Revised Day Month Year

Mixing and *CP* violation in charm meson decays provide a unique probe of possible physics beyond the standard model. In this paper, we give a brief review of the current measurements from the *BABAR* experiment.

Keywords: Charm; CP violation; Mixing.

PACS numbers: 11.30.Er, 13.25.Ft, 14.40.Lb

1. Introduction

In the standard model (SM), the mixing of neutral D mesons is due to the fact that their mass eigenstates ($|D_{1,2}\rangle$) are not the same as the flavor eigenstates (D^0, $\overline{D}^0$). They can be expressed as:

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle, \tag{1}$$

where the complex parameters p and q are obtained from diagonalizing the $D^0 - \overline{D}^0$ mass matrix and $|p|^2 + |q|^2 = 1$ under the assumption of CPT conservation. If CP violation (CPV) in mixing is neglected, p becomes equal to q, so $|D_{1,2}\rangle$ become CP eigenstates, $CP|D_\pm\rangle = \pm|D_\pm\rangle$, and

$$|D_\pm\rangle = \frac{1}{\sqrt{2}}[|D^0\rangle \pm |\overline{D}^0\rangle]. \tag{2}$$

The mixing effects can be quantified with two dimensionless parameters x and y, defined as:

$$x \equiv \frac{m_1 - m_2}{\Gamma}, \quad y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma}, \tag{3}$$

where $m_{1,2}$ and $\Gamma_{1,2}$ are the mass and widths of the states $D_{1,2}$ respectively, and $\Gamma = (\Gamma_1 + \Gamma_2)/2$.

In the SM, mixing can occur through short-range box-diagram process, and through long-range rescattering processes via intermediate hadronic states. The

Work supported in part by US Department of Energy contract DE-AC02-76SF00515.

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former are highly suppressed by the GIM mechanism or by $|V_{ub}V_{cb}|^2$. The latter are difficult to calculate precisely and can be as large as a percent level. As for the CPV in the charm meson decays, it has been predicted to be rather small in the SM. Significant *CP* violation in the charm meson decays or large mixing parameters (Eg: $x \gg 0$ or $y \gg 0$) would be a signature for new physics (NP) beyond the SM.

2. Measurement of Mixing and CPV in WS D^0 Decays

One typical approach to study mixing and CPV in charm meson decays is to examine the decay time distribution of the wrong sign (WS) D^0 decay, such as $D^0 \to K^+\pi^-$ from the D^{*+} decay [1]. The WS decay can occur via mixing, where an initially pure D^0 oscillates to become a $\overline{D}^0$, then undergoes a Cabibbo-favored (CF) decay to $K^+\pi^-$; or it can occur via doubly-Cabbibo-suppressed (DCS) decay. The D^0 meson is reconstructed in the decay $D^{*+} \to D^0\pi^+$, the charge of the soft pion from D^{*+} decay indicates the initial flavor of the D^0 meson. Since the mixing rate is small and under the assumption of no CPV, the time-dependent decay rate distribution can be written as:

$$\Gamma(D^0 \to K^+\pi^-) \propto R_D + y'\sqrt{R_D}(\Gamma t) + \frac{x'^2 + y'^2}{4}(\Gamma t)^2, \qquad (4)$$

where R_D is the ratio of DCS and CF decay rates, $x' = x\cos\delta_D + y\sin\delta_D$, $x' = -x\sin\delta_D + y\cos\delta_D$, and δ_D is the strong phase difference between DCS and CF amplitudes. When allowing for CPV, the form of Eq. 4 remains the same but has separate coefficients $R_D^{\pm}$, $x'^2_{\pm}$ and $y'^2_{\pm}$ for D^0 and $\overline{D}^0$ decays.

Similarly, the mixing parameters of other WS hadronic decays can be also extracted from their time-dependent rate distribution in a similar fashion. For a multi-body decay 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 a time-dependent amplitude fit, since the distributions of the DCS and CF decays differ. However, one must be careful: the mixing parameter x' and y' measured in $D^0 \to K^+\pi^-\pi^0$ can not be directly compared to the ones in the $D^0 \to K^+\pi^-$ decay, since their strong phase differences δ_D are not equal.

Table 1. Summary of the measurements [2,3] of mixing and *CP* violation in $D^0 \to K^+\pi^-$ and $D^0 \to K^+\pi^-\pi^0$ from *BABAR*.

Fit Type	$D^0 \to K^+\pi^-$ $[10^{-3}]$	$D^0 \to K^+\pi^-\pi^0$ $[10^{-2}]$
No CPV	$x'^2 = -0.22 \pm 0.30(\text{stat}) \pm 0.21(\text{syst})$	$x''^2 = 2.61^{+0.57}_{-0.68}(\text{stat}) \pm 0.39(\text{syst})$
	$y'^2 = 9.7 \pm 4.4(\text{stat}) \pm 3.1(\text{syst})$	$y''^2 = -0.06^{+0.55}_{-0.64}(\text{stat}) \pm 0.34(\text{syst})$
CPV allowed	$x'^2_+ = -0.24 \pm 0.43(\text{stat}) \pm 0.30(\text{syst})$	$x''^2_+ = 2.53^{+0.54}_{-0.63}(\text{stat}) \pm 0.39(\text{syst})$
	$x'^2_- = -0.20 \pm 0.41(\text{stat}) \pm 0.29(\text{syst})$	$x''^2_+ = 3.55^{+0.73}_{-0.83}(\text{stat}) \pm 0.65(\text{syst})$
	$y'^2_+ = 9.9 \pm 6.4(\text{stat}) \pm 4.5(\text{syst})$	$y''^2_+ = -0.05^{+0.63}_{-0.67}(\text{stat}) \pm 0.50(\text{syst})$
	$y'^2_- = 9.6 \pm 6.1(\text{stat}) \pm 4.3(\text{syst})$	$y''^2_+ = -0.54^{+0.40}_{-1.16}(\text{stat}) \pm 0.41(\text{syst})$

Based on a 384 fb^{-1} data sample, the *BABAR* experiment performed measurements [2,3] of mixing parameters and searched for CPV in both $D^0 \to K^+\pi^-$ and

$D^0 \to K^+\pi^-\pi^0$. The results are summarized in Table 1. Both measurements find mixing signals with a significance of more than $3\,\sigma$, and see no evidence of CPV.

3. Measurement of Mixing and CPV in $D^0 \to K^0_S\pi^+\pi^-, K^0_S K^+K^-$

Without the knowledge of the strong phase difference, the mixing parameter x and y can not be extracted from the measurements in the decay $D^0 \to K^+\pi^-$ and $D^0 \to K^+\pi^-\pi^0$. This ambiguity can be resolved by a time-dependent amplitude analysis [4] using the decay $D^0 \to K^0_S\pi^+\pi^-$ and $D^0 \to K^0_S K^+K^-$. Because both the decay final states are self-conjugate states that include *CP*-even and *CP*-odd eigenstates, it allows the relative phases to be determined. As a result, the mixing parameter x and y can be measured directly.

With 469 fb^{-1} of data sample, BABAR performed a measurement [5] of mixing parameters using the decay $D^0 \to K^0_S\pi^+\pi^-$ and $D^0 \to K^0_S K^+K^-$. We found that

$$x = (0.16 \pm 0.23 \pm 0.12 \pm 0.08)\%, \quad y = (0.57 \pm 0.20 \pm 0.13 \pm 0.07)\%, \tag{5}$$

where the first error is the statistical uncertainty, the second error is the systematic uncertainty and the third one is the uncertainty due to the Dalitz models. We also repeated the fit by allowing for CPV and saw no evidence of CPV.

4. Measurement of Mixing in D^0 Lifetime difference

D^0 mixing can be measured by comparing the lifetime extracted from the analysis of D^0 decays into $K^-\pi^+$ and $h^+h^-(h = K, \pi)$ final states. The $K^-\pi^+$ is a mixed *CP*-even and *CP*-odd final state, and h^+h^- is a *CP*-even final state. Thus we have

$$y \approx y_{CP} \approx \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to h^+h^-)} - 1, \tag{6}$$

where τ is the measured D^0 lifetime in the $K^-\pi^+$ and h^+h^- final states. BABAR performed a lifetime ratio measurement between $D^0 \to K^-\pi^+$ and $D^0 \to K^+K^-$ final states using a 384 fb^{-1} data sample [6,7]. We found that

$$y_{CP} = (1.16 \pm 0.22(\text{stat}) \pm 0.18(\text{syst}))\%. \tag{7}$$

The significance of this result from no-mixing hypothesis is $4.1\,\sigma$.

5. Measurement of Time-Integrated *CP* Asymmetries

Another method to search for CPV is to measure the time-integrated *CP* asymmetry (A_{CP}) of D meson decay to a given final state f:

$$A_{CP} = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}, \tag{8}$$

where Γ is the partial decay width for this decay. Many searches for time-integrated *CP* asymmetries have been performed by both BABAR and Belle experiments and no evidence of CPV has been seen yet. So far, all the measurements have been limited by the statistical and systematic uncertainties.

Most recently, the *BaBar* experiment performed a measurement of time-integrated *CP* asymmetry in the decay $D^+ \to K_S^0\pi^+$ [8]. In the decay $D^+ \to K_S^0\pi^+$, the SM predicts A_{CP} to be $(-0.332 \pm 0.006)\,\%$, due to CPV in $K^0 - \overline{K}^0$ mixing [9]. However, contributions from non-SM processes may reduce the value of A_{CP} or enhance it up to the level of one percent [10,11]. A significant deviation of the A_{CP} measurement from the SM expectation would be evidence for the presence of NP beyond the SM. Due to the smallness of the predicted value from the SM, this measurement requires high statistics and precise control of the systematic uncertainties.

We optimize our signal reconstruction efficiency and background rejection by using a a Boosted Decision Tree algorithm. With a 469 fb^{-1} data sample, we reconstruct $(807 \pm 0.1) \times 10^3$ signal events.

One largest systematic uncertainty in the search for time-integrated *CP* asymmetries is the differences in the charged track reconstruction efficiencies. In this analysis we have developed a data-based method to determine the charge asymmetry in track reconstruction as a function of the magnitude of the track momentum and its polar angle. Since B mesons are produced in the process $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ nearly at rest in the CM frame and decay isotropically in the B rest frame, these events provide a high statistics control sample essentially free of any physics-induced charge asymmetry. However, data recorded at the $\Upsilon(4S)$ resonance also include continuum production $e^+e^- \to q\overline{q}$ $(q = u, d, s, c)$, where there is a non-negligible forward-backward asymmetry due to the interference between the single virtual photon process and other production processes, as described above. The continuum contribution is estimated using the off-resonance data rescaled to the same luminosity as the on-resonance data sample. Subtracting the rescaled off-resonance sample from the on-resonance one, we obtain the number of reconstructed tracks corresponding to the B meson decays only. Therefore, the relative detection and identification efficiencies of the positively and negatively charged particles for given selection criteria can be determined using the numbers of positively and negatively reconstructed tracks directly from data.

Using samples, respectively, of 8.5 fb^{-1} on-resonance and 9.5 fb^{-1} off-resonance data and applying the same charged pion track selection criteria used in the reconstruction of $D^+ \to K_S^0\pi^+$ decays we obtain a sample of more than 20 million tracks after the subtraction of the off-resonance sample. We use this sample to produce a map for the ratio of detection efficiencies for π^+ and π^- as a function of the track-momentum magnitude and $\cos\theta$, where θ is the polar angle of the track in the laboratory frame. With this new method, we were able to control the total systematical uncertainty in the measurement to be less than 0.1 %, and obtained:

$$A_{CP}(D^0 \to K_S^0\pi^+) = (-0.44 \pm 0.13(\text{stat}) \pm 0.10(\text{syst}))\,\%. \tag{9}$$

This measurement is the most precise single measurement of time-integrated *CP* asymmetry in charm meson decays so far. The method we developed to measure the asymmetries in charged track reconstruction efficiencies can be used as a general method in other similar measurements.

6. Search for *CP* Violation using *T*-odd Correlations

Recently the *BABAR* experiment performed a search for CPV [12] by exploring the T-odd correlation in the decay $D^0 \to K^+K^-\pi^+\pi^-$. We define a kinematic triple product correlation $C_T = \vec{p}_{K^+} \cdot (\vec{p}_{\pi+} \times \vec{p}_{\pi^-})$, where each $\vec{p}_i$ is a momentum vector of one of the particles in the decay. The product is odd under time-reversal (T) with the assumption of CPT invariance, thus T-violation is a signal of CPV. A T-odd observable is then defined as

$$\mathcal{A}_T = \frac{1}{2}(A_T - \bar{A}_T), \tag{10}$$

where A_T and $\bar{A}_T$ are defined as

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}, \quad \bar{A}_T = \frac{\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0)}{\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)} \tag{11}$$

With a 470 fb^{-1} data sample, *BABAR* measured that

$$\mathcal{A}_T = (1.0 \pm 5.1(\text{stat}) \pm 4.4(\text{syst})) \times 10^{-3}. \tag{12}$$

The result is consistent with the SM expectation.

7. Conclusion

Measurement of mixing and CPV in charm meson decays provides new and unique opportunities to search for NP. In this paper, we give a brief review of current measurements from the *BABAR* experiments. These results constrain the possible effects of NP.

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