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D^0-$\bar{D}^0$ mixing and CPV measurements at the B-factories

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Abstract. Measurements of D^0-$\bar{D}^0$ mixing and CP violation in D^0 decays are interesting as any difference with respect to the Standard Model prediction would be a signature of new physics. We report on recent searches and measurements of D^0-$\bar{D}^0$ mixing and CP violation in charm meson decays at BaBar and Belle experiments. In particular, the D^0-$\bar{D}^0$ mixing parameters in $D^0 \to \pi^+\pi^-\pi^0$ are measured by the BaBar experiment for the first time with $x = (1.5 \pm 1.2 \pm 0.6)\%$ and $y = (0.2 \pm 0.9 \pm 0.5)\%$. The first T-odd asymmetry measurement in $D^0 \to K_S^0\pi^+\pi^-\pi^0$ is performed at the Belle experiment with $a_{CP} = (-0.28 \pm 1.38^{+0.23}_{-0.76}) \times 10^{-3}$, which is consistent with no CP violation. The measurements of CP asymmetry in $D^0 \to K_S^0 K_S^0$ with $A_{CP} = (-2.9 \pm 5.2 \pm 2.2)\%$ and $D^+ \to \pi^+\pi^0$ with $A_{CP} = (+2.31 \pm 1.24 \pm 0.23)\%$ are also reported, which shows no CP violation.

1 Introduction

The cross section for $e^+e^- \to \gamma^* \to c\bar{c}$ production at $\sqrt{s} \approx 10.58$ GeV is around 1.3 nb, which is comparative with that of $e^+e^- \to \Upsilon(4S)$ with 1.1 nb, so B-factories are abundant source of charm hadrons as well as B mesons. Belle and BaBar have collected an integrated luminosity of about 1 ab^{-1} and 0.5 ab^{-1} respectively, and an integrated luminosity of 1 ab^{-1} corresponds to about 6×10^8 D^* mesons, which provide a platform to study charm physics. In this proceedings, we report a measurement of D^0-$\bar{D}^0$ mixing via time-dependent Dalizt analysis (TDDA) in $D^0 \to \pi^+\pi^-\pi^0$ performed by the BaBar experiment for the first time. We also present the results of the first measurement of the T-odd moment asymmetry in the decay $D^0 \to K_S^0\pi^+\pi^-\pi^0$; the branching fractions and CP asymmetry in $D^0 \to K_S^0 K_S^0$; and the CP asymmetry in $D^+ \to \pi^+\pi^0$.

2 D^0-$\bar{D}^0$ mixing and CP violation

In the Standard Model (SM), the mixing phenomenon of D^0-$\bar{D}^0$ system, the only up-type quark meson system, is an example of flavor changing neutral current (FCNC) process. D^0-$\bar{D}^0$ mixing has contributions from short-distance and long-distance interactions, while CKM matrix and GIM mechanism [1] strongly suppress FCNC to $< 10^{-3}$, long-distance and SU(3) flavor breaking increase it to 10^{-2} [2]. Measurements of D^0-$\bar{D}^0$ mixing imply constraints on possible contributions from new physics (NP) processes beyond SM.

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The oscillation of neutral meson system originates from the difference between flavor and mass eigenstates of the meson-anti-meson system. The time evolution of the D^0-$\bar{D}^0$ system is described by the Schrödinger equation

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}, \tag{1}$$

where the $\mathbf{M}$ and $\mathbf{\Gamma}$ are Hermitian matrices. The two mass eigenstates D_1 and D_2 of effective Hamiltonian matrix are given by the superposition of flavor eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$. The coefficients p and q satisfy $(p^2 + q^2) = 1$ if CPT is conserved. The probability of D^0 meson transform into $\bar{D}^0$ can be described by mixing parameters x and y.

$$x = \frac{M_1 - M_2}{\bar{\Gamma}} = \frac{\Delta M}{\bar{\Gamma}}, y = \frac{\Gamma_1 - \Gamma_2}{2\bar{\Gamma}} = \frac{\Delta\Gamma}{2\bar{\Gamma}}. \tag{2}$$

where $M_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths of mass eigenstates D_1 and D_2 and $\bar{\Gamma} = \frac{\Gamma_1+\Gamma_2}{2}$.

In the SM, charge-parity violation (CPV) in charm meson decays is predicted to be very small $O(10^{-3})$. Any enhancement with respect to the SM prediction can be due to new particles or new interactions which are not included in the SM [3]. In general, there are three types of CP violation: 1) direct CPV in decay: $\bar{A}_{\bar{f}}/A_f \neq 1$; 2) CPV in mixing: $|q/p| \neq 1$; 3) CPV in interference between decays with and without mixing: $\arg(q/p) \neq 0$.

2.1 Mixing in $D^0 \to \pi^+\pi^-\pi^0$ via TDDA at BaBar

The global fits that determine world average mixing and CP violation parameter values from different experiments have been summarized by Heavy Flavor Averaging Group (HFLAV) [4], and the hypothesis of no-mixing ($x = 0$, $y = 0$) have been excluded with more than 11.5σ confidence level, assuming CPV is allowed. Even though many important results of D^0-$\bar{D}^0$ mixing in D^0 decay channels have been contributed significantly by B-factories and other experiments, only one (three) decay channels have reached the observation (evidence) confidence level of D^0-$\bar{D}^0$ mixing. More decay channels or larger samples need to be studied at different experiments.

Recently, BaBar performed the measurement on the D^0-$\bar{D}^0$ mixing parameters for the first time using a time-dependent amplitude analysis of the decay $D^0 \to \pi^+\pi^-\pi^0$ [5], based on a dataset with an integrated luminosity of 468.1 fb^{-1}. The time-integrated Dalitz plots for the signal region data are shown in Fig. 1 (a), the $m^2_{\pi^\pm\pi^0}$ and $m^2_{\pi^+\pi^-}$ projections of the data and fit are shown in Fig. 1 (b)-1(d). The measured D^0 lifetime is $\tau_D = 410.2 \pm 3.8$ fs, which agrees with the world average of (410.1 ± 1.5) fs. The measured mixing parameters are $x = (1.5 \pm 1.2 \pm 0.6)\%$ and $y = (0.2 \pm 0.9 \pm 0.5)\%$, where the quoted uncertainties are statistical and systematic, respectively. Considering this dominant statistical uncertainties can be reduced with larger datasets, Belle II experiment can achieve a preciser result with 50 ab^{-1} data [6].

2.2 T-odd asymmetry in $D^0 \to K^0_S\pi^+\pi^-\pi^0$ at Belle

The self-conjugate decay $D^0 \to K^0_S\pi^+\pi^-\pi^0$ has a large branching fraction of 5.2%, which allows for a precise test of CP symmetry as a sample of $O(10^6)$. MARK III collaboration studied it with a sample of 140 events previously [7]. Here, we present the first measurement of the T-odd asymmetry in $D^0 \to K^0_S\pi^+\pi^-\pi^0$, which is sensitive to CP violation via the CPT theorem, based on a data sample with integrated luminosity 966 fb^{-1} [8].

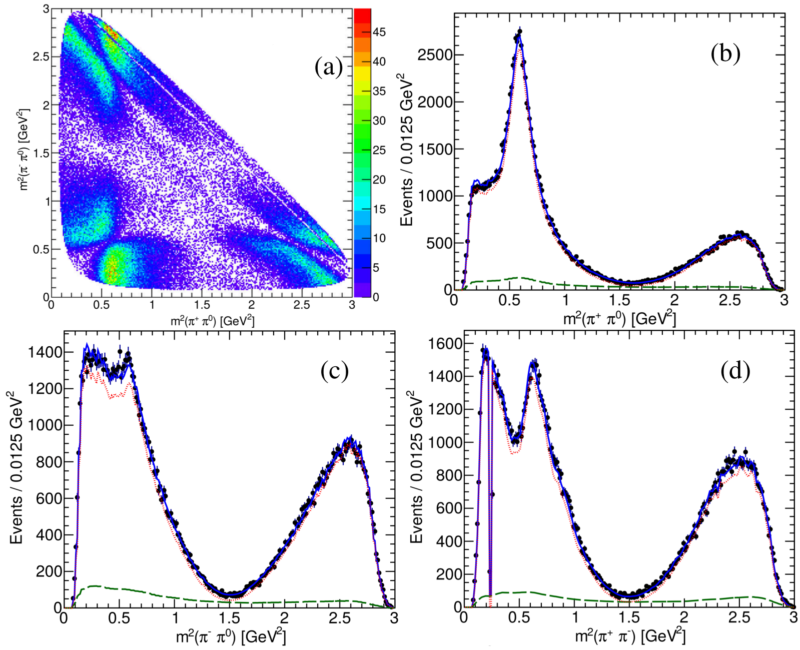

Figure 1. The Dalitz plot (a) of $D^0 \to \pi^+\pi^-\pi^0$ decay and the time-dependent Dalitz fit result of the Dalitz variables projections for $m^2_{\pi^-\pi^0}$(b), $m^2_{\pi^+\pi^0}$ (c) and $m^2_{\pi^+\pi^-}$ (d).

The measurement is performed by constructing the observable $C_T = \mathbf{p}_{\mathbf{K^0_S}} \cdot (\mathbf{p}_{\pi^+} \times \mathbf{p}_{\pi^-})$, which is displayed in Fig. 2 (a), where $\mathbf{p}_{\mathbf{K^0_S}}$, $\mathbf{p}_{\pi^+}$ and $\mathbf{p}_{\pi^-}$ are the momenta of the D^0 daughters. Similarly, the CP-conjugate observable $\bar{C}_T$ can be defined by $\bar{D}^0$ daughter particles. Then the CPV sensitive asymmetry is defined as $a_{CP}^{T-odd} = \frac{1}{2}(A_T - \bar{A}_T)$, where A_T and $\bar{A}_T$ are the two asymmetry parameters for D^0 and $\bar{D}^0$, respectively.

$$A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}, \quad \bar{A}_T = \frac{\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0)}{\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)}. \tag{3}$$

For the reconstruction of D^* and D^0 decays, we use the charge of slow π to distinguish flavor of D^0 and $\bar{D}^0$. The signal yield is determined by a two-dimensional un-binned maximum likelihood fit to invariant mass of D^0 (M_{D^0}) and invariant mass difference between D^* and D^0, $\Delta M \equiv M_{D^*} - M_{D^0}$. The fit result of signal-enhanced logarithmic distributions of M_{D^0} and ΔM for D^0 with $C_T > 0$ is drawn in Fig. 2 (b) and (c) respectively. Finally, the T-odd moment asymmetry is $a_{CP}^{T-dd} = (-0.28 \pm 1.38^{+0.23}_{-0.76}) \times 10^{-3}$, which is consistent with no CPV. The results in various regions of $K^0_S\pi^+\pi^-\pi^0$ phase space also show no evidence for CPV. This result constitutes one of the most precise tests of CP violation in the D meson system. The measurement uncertainties are statistically dominated, and thus can be improved further with the data from the Belle II experiment.

2.3 CP asymmetry in $D^0 \to K^0_S K^0_S$ at Belle

$D^0 \to K^0_S K^0_S$ is a Singly Cabibbo-suppressed decay, which is of special interest as possible interference with NP amplitudes could lead to large nonzero CPV. A recent SM based

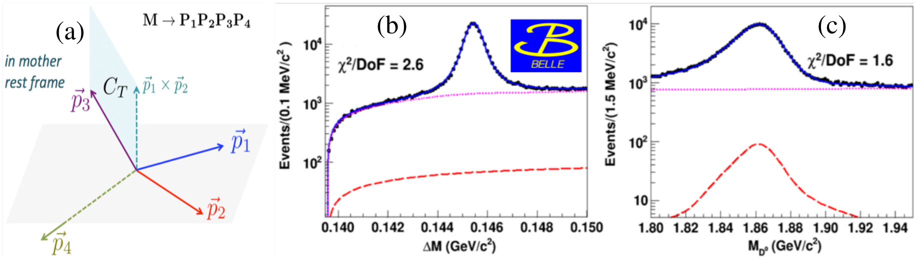

Figure 2. A schematic diagram (a) for the definition of the observable $C_T = (p_1 \times p_2) \cdot p_3$. The result of simultaneous maximum likelihood fit to the 2D distribution of ΔM (b), and M_{D0} (c) for D^0 with $C_T > 0$.

calculation gave an upper limit of 1.1% for direct CP violation [9]. The CP asymmetry of $D^0 \to K_S^0 K_S^0$ has been studied by CLEO [10], LHCb [11], and BESIII [12] reported a branching fraction for this mode with the results limited by statistics. Belle could significantly improve these measurements with an integrated luminosity of 921 fb^{-1} [13].

The branching fractions and CP asymmetry for the decay $D^0 \to K_S^0 K_S^0$ are measured, in contrast to measuring the normalization mode $D^0 \to K_S^0 \pi^0$. The measured raw asymmetry A_{raw} is a composition of CP asymmetry A_{CP}, forward-backward production asymmetry of D^0 mesons A_{FB}, asymmetry due to different detection efficiencies for positively and negatively charged pions $A_\epsilon^\pm$, and A_ϵ^K is the asymmetry originating from the distinct strong interaction of K^0 and $\bar{K}^0$ mesons with nucleons in the detector material,

$$A_{raw} = A_{CP} + A_{FB} + A_\epsilon^\pm + A_\epsilon^K. \tag{4}$$

Through a relative measurement of A_{CP} with respect to the well-measured $D^0 \to K_S^0 \pi^0$, A_{FB} and $A_\epsilon^\pm$ can be eliminated. The value of A_ϵ^K is estimated to be -0.11% [15]. The CP asymmetry of the signal mode is then expressed as

$$A_{CP}(D^0 \to K_S^0 K_S^0) = A_{raw}(D^0 \to K_S^0 K_S^0) - A_{raw}(D^0 \to K_S^0 \pi^0) + A_{CP}(D^0 \to K_S^0 \pi^0) + A_\epsilon^K, \tag{5}$$

where $A_{CP}(D^0 \to K_S^0 \pi^0) = (-0.20 \pm 0.17)\%$ is the world-average CP asymmetry of the normalization mode [14]. Then a simultaneous fit of the ΔM distributions for D^{*+} and D^{*-} , which are shown in Fig. 3, is used to calculate the raw asymmetry in $D^0 \to K_S^0 K_S^0$ and $D^0 \to K_S^0 \pi^0$. A similar procedure is performed for $D^0 \to K_S^0 \pi^0$ sample. The fitted values of A_{raw} of the $D^0 \to K_S^0 K_S^0$ and $D^0 \to K_S^0 \pi^0$ decay modes are (+0.45 ± 1.53)% and (+0.16 ± 0.14)%, respectively. The resulting time integrated CP-violating asymmetry in the $D^0 \to K_S^0 K_S^0$ decay is $A_{CP}(D^0 \to K_S^0 K_S^0) = -(0.02 \pm 1.53 \pm 0.02 \pm 0.17)\%$. For the branching fraction measurement, we use only the D^{*+} candidates that have a momentum greater than 2.5 GeV/c in the center-of-mass frame and perform the ΔM fit for $D^0 \to K_S^0 K_S^0$ and $D^0 \to K_S^0 \pi^0$ decays. The resulting branching fraction is $\mathcal{B}(D^0 \to K_S^0 K_S^0) = (1.321 \pm 0.023 \pm 0.036 \pm 0.044) \times 10^{-4}$, where the first uncertainty is statistical, the second is the systematic, and the third is due to the uncertainty on $\mathcal{B}$ of $D^0 \to K_S^0 \pi^0$. The result of A_{CP} is consistent with no CPV and improves significantly the previous measurements. The branching fraction is consistent with the world average. Both A_{CP} and $\mathcal{B}$ results are the most precise measurements for the $D^0 \to K_S^0 K_S^0$ decay.

2.4 CP asymmetry in $D^+ \to \pi^+ \pi^0$ at Belle

$D^+ \to \pi^+ \pi^0$ is also a Singly-Cabibbo-suppressed decay, which is one of the excellent candidates to probe CP violation in the charm sector. Any CP asymmetry found in these channels

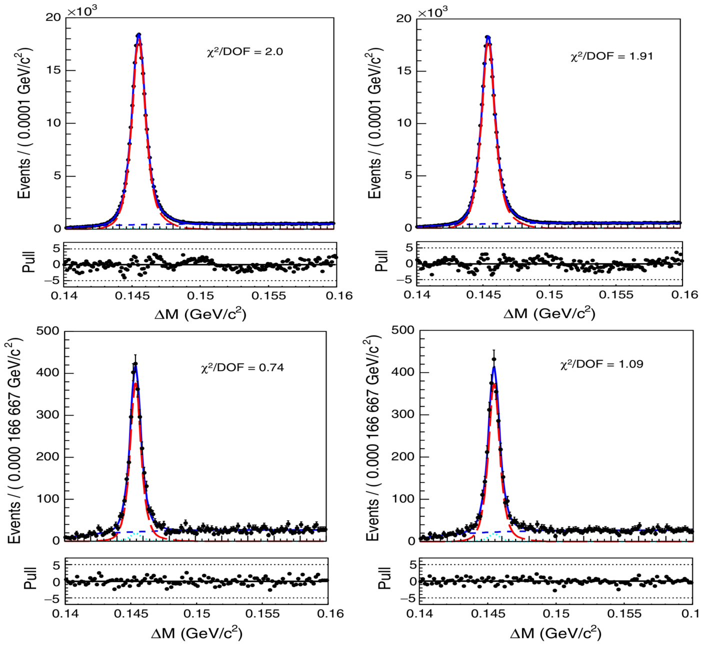

Figure 3. Distributions of the mass difference ΔM for selected D^{*+} (left) and D^{*-} (right) candidates, reconstructed from $D^0 \to K^0_S K^0_S$ (top) and $D^0 \to K^0_S \pi^0$ (bottom).

will point to NP [16]. Using 921 fb^{-1} data sample collected by Belle detector, CP asymmetry is measured via a simultaneous fit to the invariant mass of the D meson in the decay $D^+ \to \pi^+\pi^0$ [17] and the fit result is shown in Fig. 4. In this decay, the raw asymmetry of $D^+ \to \pi^+\pi^0$ is measured as $A^{\pi\pi}_{raw} = A^{\pi\pi}_{CP} + A_{FB} + A^{\pi\pm}_{\epsilon}$, where A_{FB} and $A^{\pi\pm}_{\epsilon}$ have same illustration as for Eq. (4). $A^{\pi\pi}_{CP}$ is the CP asymmetry of $D^+ \to \pi^+\pi^0$, which has been measured to be $(-0.363 \pm 0.094 \pm 0.067)\%$. The decay $D^+ \to \pi^+ K^0_S$ is chosen as the normalization channel by performing the same procedure as $D^+ \to \pi^+\pi^0$, and the CP asymmetry is obtained by $A^{\pi\pi}_{CP} = \Delta A_{raw} + A^{K\pi}_{CP}$, where the CP asymmetry for $D^+ \to \pi^+ K^0_S$ has been measured to be $A^{K\pi}_{CP} = (0.363 \pm 0.094 \pm 0.067)\%$ [18]. The raw asymmetry is obtained from the fit as $A^{\pi\pi}_{raw} = (+0.52 \pm 1.92)\%$ for a tagged D sample and $A^{\pi\pi}_{raw} = (+3.77 \pm 1.60)\%$ for an untagged D sample. For the normalization channel, the raw asymmetries are measured as $A^{K\pi}_{raw} = (-0.29 \pm 0.44)\%$ for the tagged sample and $A^{K\pi}_{raw} = (+0.25 \pm 0.17)\%$ for the untagged sample. With a combination of the two results, ΔA_{raw} is measured as $(+2.67 \pm 1.24 \pm 0.20)\%$, then $A_{CP}(D^+ \to \pi^+\pi^0)$ is determined to be $(+2.31 \pm 1.24 \pm 0.23)\%$, which is consistent no CP violation.

3 Summary

Measurements of D^0-$\bar{D}^0$ mixing and CPV play a very important and fundamental role in precise tests of the SM and searching for NP. Based on the integrated luminosity of about 1 ab^{-1} and 0.5 ab^{-1} collected by Belle and BaBar experiments, fruitful results of D^0-$\bar{D}^0$ mixing and CP violation in many D decay channels have been achieved.

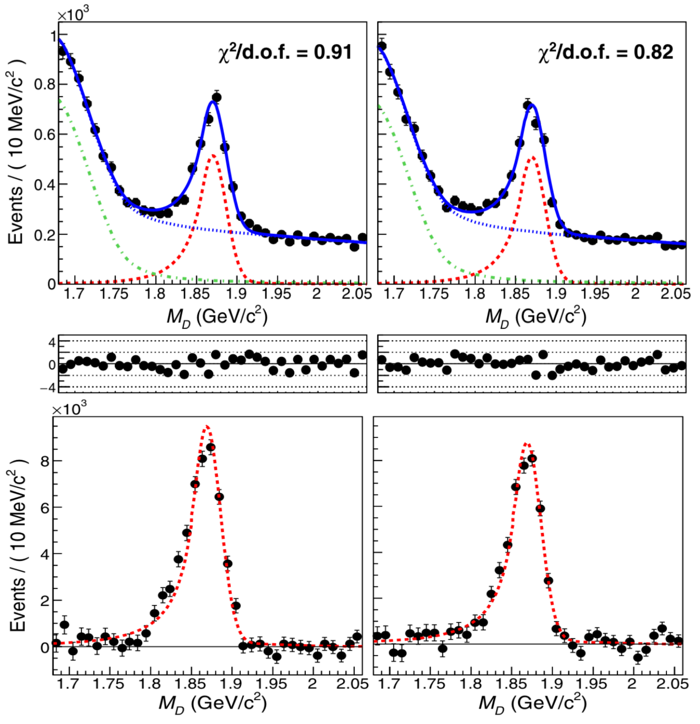

Figure 4. Distributions of invariant mass of $D \to \pi\pi$ sample for the tagged (top) and untagged (bottom), left (right) correspond to $D^{+}(D^{-})$ samples.

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