CP VIOLATION IN CHARM AND TAU AT B-FACTORIES

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Recent result of a high-statistics search for CP violation in $D^+ \to K_S\pi^+$ decay at Belle is presented. Studies of CP violation in $\tau^- \to K_S\pi^-\nu_\tau$ decay at Belle and $\tau^- \to \pi^- K_S(\geq \pi^0)\nu_\tau$ at $BABAR$ are discussed.

1 Introduction

In the standard model (SM) violation of the combined charge-conjugation and parity symmetries (CP) is described by nonzero phase in the Cabibbo-Kobayashi-Maskawa flavor-mixing matrix [1]. So far CP violation (CPV) has been experimentally observed only in the K and B meson decays. After the successfull operation of B-factories, Belle [2] and $BABAR$ [3], both collaborations are analysing the world largest data set, collected in the region of $\Upsilon(4S)$ resonance, which comprises approximately 1.7×10^9 events of $b\bar{b}$ production, 2.0×10^9 $c\bar{c}$ events and 1.4×10^9 events of tau pair production. So, B-factories should be regarded also as a charm-τ factories with a great potential in the study of CPV in charmed meson and tau decays.

CPV in the charm sector of the SM is expected to be very small, of the order of 0.1% or lower [4]. Hence, the discovery of large CPV (O(1%)) in charm would be a clear sign for the New Physics (NP) [5]. In this review recent result of the search for the direct CPV in $D^+ \to K_S\pi^+$ decay at Belle is discussed [6]. This CPV asymmetry, $A_{CP}^{D^+\to K_S\pi^+} = \frac{\Gamma(D^+\to K_S\pi^+)-\Gamma(D^-\to K_S\pi^-)}{\Gamma(D^+\to K_S\pi^+)+\Gamma(D^-\to K_S\pi^-)} = A_{CP}^{\Delta C} + A_{CP}^{\bar{K}^0}$, consists of $A_{CP}^{\bar{K}^0} = (-0.332 \pm 0.006)\%$ [7], induced by CPV in $K^0 - \bar{K}^0$ mixing, and $A_{CP}^{\Delta C} \lesssim 0.01\%$, which is determined by the SM Cabibbo-favored and doubly Cabibbo-suppressed amplitudes [5]. $A_{CP}^{D^+\to K_S\pi^+}$ is measured to be $(-0.363\pm0.094\pm0.067)\%$, which is the first evidence for CPV in charmed meson decays from a single experiment and a single decay mode.

In the leptonic sector CPV is strongly suppressed in the SM ($A_{\rm SM}^{\rm CP} \lesssim 10^{-12}$) leaving enough room to search for the effects of NP [8]. Of particular interest are strangeness changing Cabibbo-suppressed hadronic τ decays, in which large CPV could appear from a charged scalar boson exchange in some Multi-Higgs-Doublet models (MHDM) [9]. Recent studies of CPV in $\tau^- \to \pi^- K_S(\geq \pi^0)\nu_\tau$ decays at $BABAR$ [10] as well as in $\tau^- \to K_S\pi^-\nu_\tau$ decay at Belle [11] provide complementary information about sources of CPV in these hadronic decays. While the difference between τ^- and τ^+ decay angular distributions is studied at Belle to find out contribution from the charged scalar boson exchange, decay-rate asymmetry $A_{\rm CP} = \frac{\Gamma(\tau^+\to\pi^+K_S(\geq\pi^0)\nu_\tau)-\Gamma(\tau^-\to\pi^-K_S(\geq\pi^0)\nu_\tau)}{\Gamma(\tau^+\to\pi^+K_S(\geq\pi^0)\nu_\tau)+\Gamma(\tau^-\to\pi^-K_S(\geq\pi^0)\nu_\tau)}$ measured at $BABAR$ is sensitive to the CPV in the kaon sector of the SM [12,13].

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2 CP violation in $D^+ \to K_S\pi^+$ at Belle

This analysis is based on a 977 fb^{-1} data sample, which was collected in the region of $\Upsilon(nS)$ resonances ($n = 1, 2, 3, 4, 5$) with the Belle detector. Events with K_S and $\pi^\pm$ candidates are selected to form a $D^\pm$ candidate. K_S is reconstructed from $\pi^+\pi^-$ pairs, fitted to a common vertex with invariant mass of the pair to be 0.4826 GeV/$c^2 \leq M_{\pi^+\pi^-} \leq$ 0.5126 GeV/c^2. The K_S and $\pi^\pm$ candidates are approximated to a common vertex, then $D^\pm$ candidate is fitted to the e^+e^- interaction point to give the production vertex. Background from B meson decays and combinatorics was suppressed by a cut on the CMS D^+ meson momentum $p^{\rm CMS}_{D^+} > 2.5$ GeV/c ($p^{\rm CMS}_{D^+} > 3.0$ GeV/c) for the data collected at the $\Upsilon(4S)$ ($\Upsilon(5S)$) resonance. For the statistics collected below $\Upsilon(4S)$ lower momentum threshold is applied $p^{\rm CMS}_{D^+} > 2.0$ GeV/c. The main background with a broad peaking structure in the $K_S\pi$ invariant mass ($M_{K_S\pi}$) signal region comes from the misidentification of charged kaons from $D_s^+ \to K_S K^+$ decays. The asymmetry $A^{D^+\to K_S\pi^+}_{\rm rec} = (N^{D^+\to K_S\pi^+}_{\rm rec} - N^{D^-\to K_S\pi^-}_{\rm rec})/(N^{D^+\to K_S\pi^+}_{\rm rec} + N^{D^-\to K_S\pi^-}_{\rm rec})$ and the sum of the D^+ and D^- yields are directly obtained from a simultaneous fit to the D^+ and D^- candidate $M_{K_S\pi}$ distributions: $A^{D^+\to K_S\pi^+}_{\rm rec} = (-0.146 \pm 0.094)\%$, $N^{D^+\to K_S\pi^+}_{\rm rec} + N^{D^-\to K_S\pi^-}_{\rm rec} = (1738\pm2)\times10^3$. Measured asymmetry includes several contributions (neglecting the terms with product of asymmetries): $A^{D^+\to K_S\pi^+}_{\rm rec} = A^{D^+\to K_S\pi^+}_{CP} + A^{D^+}_{FB}(\cos\theta^{\rm CMS}_{D^+}) + A^{\pi^+}_{\epsilon}(p^{\rm lab}_{T\pi^+}, \cos\theta^{\rm lab}_{\pi^+}) + A_{\mathcal{D}}(p^{\rm lab}_{K_S})$. A_{CP} is independent of all kinematic variables other than K_S decay time. $A^{D^+}_{FB}$ is the forward-backward asymmetry due to $\gamma^{\rm virt}$-Z^0 interference and higher order QED corrections in $e^+e^- \to c\bar{c}$, it is an odd function of the cosine of polar angle of the D^+ momentum in the center-of-mass system (c.m.s.). $A^{\pi^+}_{\epsilon}$ is asymmetry in the detection efficiency between π^+ and π^-, it depends on the transverse momentum and the polar angle of the π^+ in the laboratory frame (lab). Difference in interactions of $\bar{K^0}$ and K^0 with materal of the detector induces the $A_{\mathcal{D}}$ asymmetry, which is a function of K_S momentum in the lab [14]. $A^{\pi^+}_{\epsilon}$ is measured in 10×10 bins of the 2D phase space ($p^{\rm lab}_{T\pi^+}$, $\cos\theta^{\rm lab}_{\pi^+}$) using $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+\pi^0$ decays. The average of $A^{\pi^+}_{\epsilon}$ over the phase space is (+0.078±0.040)%. $A_{\mathcal{D}}$ was tabulated in bins of K_S momentum in the lab, and was found to be about 0.1% after the integration over the phase space. Then $D^\pm \to K_S\pi^\pm$ candidates are weighted with a factor of $(1 \mp A^{\pi^+}_{\epsilon})(1 \mp A_{\mathcal{D}})$ in the 3D ($p^{\rm lab}_{T\pi^+}$, $\cos\theta^{\rm lab}_{\pi^+}$, $p^{\rm lab}_{K_S}$) phase space and $M_{K_S\pi}$ distributions are fitted simultaneously to extract $A^{D^+\to K_S\pi^+}_{CP}$ and $A^{D^+}_{FB}(\cos\theta^{\rm CMS}_{D^+})$ asymmetries as a functions of $|\cos\theta^{\rm CMS}_{D^+}|$, see Fig. 1. Averaging over the $|\cos\theta^{\rm CMS}_{D^+}|$ bins, the CP

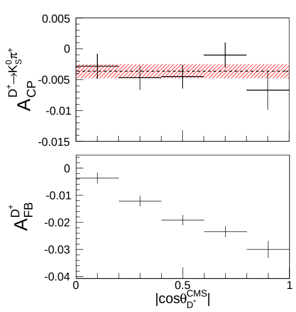

Figure 1: Measured A_{CP} (top) and A_{FB} (bottom) values as a function of $|\cos\theta^{\rm CMS}_{D^+}|$.

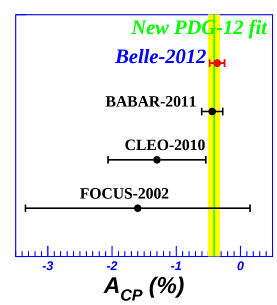

Figure 2: Summary of $A^{D^+\to K_S\pi^+}_{CP}$ measurements.

asymmetry is found to be $A^{D^+\to K_S\pi^+}_{CP} = (-0.363 \pm 0.094 \pm 0.067)\%$, which represents the first evidence for CPV in charmed meson decays from a single experiment and a single decay mode. Our result, all previous measurements and new world average are shown in Fig. 2. The measured asymmetry due to the $K^0 - \bar{K}^0$ mixing ($(-0.345 \pm 0.008)\%$) was calculated multiplying $A^{\bar{K}^0}_{CP}$ by the correction 1.040 ± 0.005 due to the acceptance effects as a function of K_S decay time [13]. After its subtraction, the CP asymmetry due to the change of charm is consistent with zero,

$A_{CP}^{\Delta C} = (-0.018 \pm 0.094 \pm 0.068)\%$.

3 CP violation in $\tau^- \to \pi^- K_S (\geq \pi^0)\nu_\tau$ at *BABAR*

This investigation is based on the data sample of about 875 million τ leptons ($\int L dt = 476$ fb^{-1}), which was collected by the *BABAR* detector in the region of $\Upsilon(4S)$ resonance. Each event is divided into the "signal" and "tag" hemispheres using event thrust axis, which is calculated considering all charged and neutral particles. Events with one prompt track and a $K_S \to \pi^+\pi^-$ candidate reconstructed in the signal hemisphere, and exactly one oppositely charged prompt track in the tag hemisphere are selected. The π^0 candidates are constructed from two photon clusters with $E_\gamma^{LAB} > 30$ MeV and the $\gamma\gamma$ invariant mass satisfying 0.115 GeV$/c^2 < M_{\gamma\gamma} < 0.150$ GeV$/c^2$ criteria. If more than three π^0 candidates are reconstructed in the signal hemisphere, the three with invariant masses closest to the π^0 mass are considered.

After all selection criteria, a total of 199064 (140602) candidates are obtained in the e-tag (μ-tag) sample. The selected sample contains signal events of $\tau^\mp \to \pi^\mp K_S(\geq \pi^0)\nu_\tau$ decay ($\simeq 79\%$) as well as events of $\tau^\mp \to K^\mp K_S(\geq \pi^0)\nu_\tau$ ($\simeq 4\%$), $\tau^\mp \to \pi^\mp K^0 \bar{K}^0 \nu_\tau$ ($\simeq 16\%$) decays and other background ($\simeq 1\%$). After the subtraction of background composed of $q\bar{q}$ and non-K_S τ decays, the decay-rate asymmetry is measured to be $(-0.32 \pm 0.23)\%$ (e-tag sample) and $(-0.05 \pm 0.27)\%$ (μ-tag sample). Effects of forward-backward asymmetry in the $e^+e^- \to \tau^+\tau^-$ production and the detector induced asymmetry are studied with experimental data sample of $\tau^\mp \to h^\mp h^- h^+ (\geq 0\pi^0)\nu_\tau$ ($h = \pi,\ K$; $K_S \to \pi^+\pi^-$ is excluded). The asymmetry correction due to the different nuclear interactions of $\bar{K}^0$ and K^0 with materal of the detector [14] is found to be $(0.07 \pm 0.01)\%$ for both e-tag and μ-tag samples. After all corrections applied, the weighted average asymmetry is $A = (-0.27 \pm 0.18 \pm 0.08)\%$. The decay-rate asymmetry for the $\tau^- \to \pi^- K_S(\geq \pi^0)\nu_\tau$, $A_{\rm CP} = (-0.36 \pm 0.23 \pm 0.11)\%$, is calculated from the measured asymmetry applying 0.75 ± 0.04 dilution correction coming from $\tau^- \to K^- K_S(\geq \pi^0)\nu_\tau$ and $\tau^- \to \pi^- K^0 \bar{K}^0 \nu_\tau$ decays.

Taking into account selection efficiency as a function of $K_S \to \pi^+\pi^-$ decay time the SM decay-rate asymmetry due to the $K^0 - \bar{K}^0$ mixing is calculated to be $A_{\rm CP}^{K^0} = (+0.36 \pm 0.01)\%$ [13]. As a result the decay-rate asymmetry $A_{\rm CP} = (-0.36 \pm 0.23 \pm 0.11)\%$ in the $\tau^- \to \pi^- K_S(\geq \pi^0)\nu_\tau$ decay mode is 2.8 standard deviations from the SM prediction.

4 CP violation in $\tau^- \to K_S \pi^- \nu_\tau$ at Belle

The $K_S\pi^-$ hadronic current in the matrix element of $\tau^- \to K_S(q_1)\pi^-(q_2)\nu_\tau$ decay is parametrized by vector ($F_V(Q^2)$) and scalar ($F_S(Q^2)$) form factors ($Q = q_1 + q_2$):

$$J^\mu = F_V(Q^2)\left(g^{\mu\nu} - \frac{Q^\mu Q^\nu}{Q^2}\right)(q_1 - q_2)_\nu + F_S(Q^2)Q^\mu$$

As a result the differential decay width in the $K_S\pi^-$ rest frame is given by ($d\omega = dQ^2 d\cos\theta d\cos\beta$):

$$\frac{d\Gamma}{d\omega} = (A(Q^2) + B(Q^2)(3\cos^2\beta - 1)(3\cos^2\psi - 1))|F_V(Q^2)|^2 + C(Q^2)M_\tau^2|F_S|^2 + D(Q^2)\cos\beta\cos\psi\Re(F_V \overset{*}{F}_S),$$

where β, θ and ψ angles are evaluated from the measured parameters of the final hadrons. $A(Q^2)$, $B(Q^2)$, $C(Q^2)$ and $D(Q^2)$ functions can be calculated within SM. The effect of the additional exchange of a charged scalar boson is described by modified scalar form factor: $F_S(Q^2) \to \tilde{F}_S(Q^2) = F_S(Q^2) + \frac{\eta_S}{m_\tau}F_H(Q^2)$, where $F_H(Q^2) = \frac{Q^2}{m_u - m_s}F_S(Q^2)$ denotes the form factor for the scalar boson exchange (m_u and m_s are the up and strange quark masses). η_S is the corresponding dimensionless complex coupling constant, which is transformed under CP conjugation as $\eta_S \to \eta_S^*$. As a result the CP violating quantity is defined as $\frac{d\Gamma_{\tau^-}}{d\omega} - \frac{d\Gamma_{\tau^+}}{d\omega} =$

Table 1: CP asymmetry A^{CP} measured in 4 bins of the hadronic mass $W = \sqrt{Q^2}$.

W (GeV/c^2)	Observed $A^{CP}(10^{-3})$	Corr. $A^{CP}(10^{-3})$	Backgr. subtr. $A^{CP}(10^{-3})$
0.625 − 0.890	-0.1 ± 2.1	5.2 ± 2.1	$7.9 \pm 3.0 \pm 2.8$
0.890 − 1.110	-2.7 ± 1.7	1.6 ± 1.7	$1.8 \pm 2.1 \pm 1.4$
1.110 − 1.420	-5.1 ± 4.7	-3.5 ± 4.7	$-4.6 \pm 7.2 \pm 1.7$
1.420 − 1.775	9.3 ± 12.1	9.6 ± 12.1	$-2.3 \pm 19.1 \pm 5.5$

$-\frac{2}{m_\tau} D(Q^2)\cos\beta\cos\psi\Im(F_V \overset{*}{F}_S)\Im(\eta_S)$. Therefore, to extract this term experimentally we define asymmetry, which is a difference between the mean values of $\cos\beta\cos\psi$ for τ^- and τ^+ events evaluated in bins of Q^2:

$$A_i^{CP} = \frac{\int \cos\beta\cos\psi \left(\frac{d\Gamma_{\tau^-}}{d\omega} - \frac{d\Gamma_{\tau^+}}{d\omega}\right) d\omega}{\frac{1}{2}\int \left(\frac{d\Gamma_{\tau^-}}{d\omega} + \frac{d\Gamma_{\tau^+}}{d\omega}\right) d\omega} \simeq \langle\cos\beta\cos\psi\rangle_{\tau^-} - \langle\cos\beta\cos\psi\rangle_{\tau^+}$$

At Belle this CPV search is performed as a blind analysis, it is based on a 699 fb^{-1} data sample, which was collected at the $\Upsilon(nS)$ resonances ($n = 3, 4, 5$). Events with one charged track from an electron, muon or pion in one hemisphere (tag side) and a charged pion and a $K_S \to \pi^+\pi^-$ candidate in the other hemisphere (signal side) are selected. In total, $(162.2 \pm 0.4) \times 10^3$ $\tau^+ \to K_S\pi^+\bar{\nu}_\tau$ and $(162.0 \pm 0.4) \times 10^3$ $\tau^- \to K_S\pi^-\nu_\tau$ candidates were found with $(22.1 \pm 3.6)\%$ contribution from background processes. Effects of forward-backward asymmetry in the $e^+e^- \to \tau^+\tau^-$ production (O(10^{-4})) as well as detector induced differences between π^+ and π^- reconstruction efficiencies (O(10^{-3})) were studied using experimental events of $\tau^\pm \to \pi^\pm\pi^+\pi^-\nu_\tau$ decay. The observed CP asymmetry in the $\tau^\pm \to K_S\pi^\pm\nu_\tau$ candidate sample is shown in Table 1 before and after applying all corrections, final CP asymmetry after background subtraction is shown in the last column. From the measured values of A^{CP} the upper limit for the CPV parameter $\Im(\eta_S)$ is extracted at 90% confidence level $|\Im(\eta_S)| < 0.026$, which is about one order of magnitude better than the previous measurement [15]. Using this limit parameters of the MHDM models can be constrained as $|\Im(XZ^*)| < 0.15\ M^2_{H^\pm}/(1\,\mathrm{GeV}^2/c^4)$, where $M_{H^\pm}$ is the mass of the lightest charged Higgs boson, the complex constants Z and X describe the coupling of the Higgs boson to the τ and ν_τ and the u and s quarks, respectively.

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