Search for CP Violation in $D^0 \to \pi^0\pi^0$ Decays

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We search for CP violation in neutral charm meson decays using a data sample with an integrated luminosity of 966 fb^{-1} collected with the Belle detector at the KEKB e^+e^- asymmetric-energy collider. The asymmetry obtained in the rate of D^0 and $\bar{D}^0$ decays to the $\pi^0\pi^0$ final state, $[-0.03 \pm 0.64(\mathrm{stat}) \pm 0.10(\mathrm{syst})]\%$, is consistent with no CP violation. This constitutes an order of magnitude improvement over the existing result. We also present an updated measurement of the CP asymmetry in the $D^0 \to K^0_S\pi^0$ decay: $A_{CP}(D^0 \to K^0_S\pi^0) = [-0.21 \pm 0.16(\mathrm{stat}) \pm 0.07(\mathrm{syst})]\%$.

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Within the standard model (SM), CP violation in charm decays [1–3] is expected to be very small and thus challenging to observe experimentally. Observing such CP violation could indicate new physics. The $D^0 \to \pi^0\pi^0$ decay proceeds via a singly Cabibbo-suppressed (SCS) amplitude, which is expected to have enhanced interference with new physics amplitudes. Such interference could generate a large CP violation effect. An early observation by LHCb [4] suggested a 3.5 standard deviation (σ) effect on the difference of direct CP asymmetries (ΔA_{CP}) between $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays that was later supported by the CDF experiment [5]. At the end of 2012, the world average [6] for ΔA_{CP} was 4.6σ away from zero. This triggered much theoretical activity [7] in an attempt to explain the effect.

In the SM, CP violation in SCS charm decays arises due to interference between the tree and loop (penguin) amplitudes and is suppressed by $O(V_{cb}V_{ub}/V_{cs}V_{us}) \sim 10^{-3}$, where V_{ij} are the elements of the Cabibbo-Kobayashi-Maskawa matrix [8]. The uncertainties on these order-of-magnitude estimates are, however, large [3]. Although a large ΔA_{CP} could be explained by non-SM physics, it may be simply due to an unexpectedly enhanced CP-violating SM $c \to u$ penguin amplitude. In the latter case, one expects

fractional-percent CP asymmetries in other SCS two-body decays such as $D^0 \to \pi^0\pi^0$ [9–12]. Recently, new measurements of ΔA_{CP} have been performed [13,14], and the current world average is 2.3σ away from zero [6]. The only search for CP violation in $D^0 \to \pi^0\pi^0$ was performed by the CLEO Collaboration using 13.7 fb^{-1} of data [15]; the result was $A_{CP} = (+0.1 \pm 4.8)\%$.

In this Letter, we measure the time-integrated CP-violating asymmetry (A_{CP}) in neutral charm meson decays to a pair of neutral pions, $D^0 \to \pi^0\pi^0$ [16]. We also update our $D^0 \to K^0_S\pi^0$ result [17] using Belle's full data sample. The SM predicts a nonzero CP asymmetry in final states containing a neutral kaon due to K^0-$\bar{K}^0$ mixing, even if no CP-violating phase exists in the charm decay amplitudes. The expected magnitude for this type of asymmetry is $A^{\bar{K}^0}_{CP} = (-0.339 \pm 0.007)\%$ [18].

The charge of the accompanying low-momentum or "slow" pion π^+_s in the decay $D^{*+} \to D^0\pi^+_s$ [16] identifies the flavor of the neutral charm meson (whether it is a D^0 or a $\bar{D}^0$) at its production. The measured asymmetry

$$A_{\rm rec} = \frac{N^{D^{*+}\to D^0\pi^+_s}_{\rm rec} - N^{D^{*-}\to \bar{D}^0\pi^-_s}_{\rm rec}}{N^{D^{*+}\to D^0\pi^+_s}_{\rm rec} + N^{D^{*-}\to \bar{D}^0\pi^-_s}_{\rm rec}}, \quad (1)$$

where $N_{\rm rec}$ is the number of reconstructed signal events, includes three contributions: the underlying CP asymmetry A_{CP}, the forward-backward asymmetry ($A_{\rm FB}$) due to γ-Z^0 interference in $e^+e^- \to c\bar{c}$ and higher-order QED effects [19], and the detection asymmetry between positively and negatively charged pions ($A^{\pi_s}_\epsilon$). The last contribution depends on the transverse momentum $p^{\pi_s}_T$ and polar angle θ^{π_s} of the slow pion and is independent of the D^0 decay final state. To estimate $A^{\pi_s}_\epsilon$, we use the Cabibbo-favored decay $D^0 \to K^-\pi^+$ ("untagged") and $D^{*+} \to D^0\pi^+_s \to K^-\pi^+\pi^+_s$ ("tagged"), and we assume the same $A_{\rm FB}$ for D^{*+} and D^0 mesons [20]. By subtracting the measured asymmetries in these two decay modes, we directly obtain the $A^{\pi_s}_\epsilon$ correction factor [$O(0.1\%)$]. After $A_{\rm rec}$ is corrected for $A^{\pi_s}_\epsilon$, one is left with

$$A^{\rm cor}_{\rm rec} = A_{CP} + A_{\rm FB}(\cos\theta^*). \quad (2)$$

While A_{CP} is independent of all kinematic variables, $A_{\rm FB}$ is an odd function of the cosine of the D^{*+} polar angle θ^* in the center of mass (c.m.) system. We thus extract A_{CP} and $A_{\rm FB}$ using

$$A_{CP} = [A^{\rm cor}_{\rm rec}(\cos\theta^*) + A^{\rm cor}_{\rm rec}(-\cos\theta^*)]/2, \quad (3)$$

and

$$A_{\rm FB} = [A^{\rm cor}_{\rm rec}(\cos\theta^*) - A^{\rm cor}_{\rm rec}(-\cos\theta^*)]/2. \quad (4)$$

The analysis is based on a data sample corresponding to an integrated luminosity of 966 fb^{-1} collected at the $\Upsilon(nS)$ resonances ($n = 1, 2, 3, 4, 5$) or 60 MeV below the $\Upsilon(4S)$ resonance with the Belle detector [21] at the KEKB asymmetric-energy e^+e^- collider [22]. In the following, the samples taken at or below the $\Upsilon(4S)$ resonance will be referred to as $\Upsilon(4S)$, while the sample recorded at the $\Upsilon(5S)$ is considered separately. The detector components relevant for our study are a tracking system comprising a silicon vertex detector (SVD) and a 50-layer central drift chamber (CDC), a particle identification (PID) system that consists of a barrel-like arrangement of time-of-flight scintillation counters (TOF) and an array of aerogel threshold Cherenkov counters (ACC), and a CsI(Tl) crystal-based electromagnetic calorimeter (ECL). All these components are located inside a superconducting solenoid coil that provides a 1.5 T magnetic field.

We use Monte Carlo (MC) simulated events representing a luminosity 6 times that of the data to devise selection criteria and investigate possible sources of background. The selection optimization is performed by minimizing the expected statistical error on $A_{\rm rec}$, where the branching fraction of $D^0 \to \pi^0\pi^0$ is set to 8×10^{-4} [23] in MC simulations. The level of background is obtained by appropriately scaling the number of events observed in a data sideband of the reconstructed D^* mass.

Candidates for the $K^0_S \to \pi^+\pi^-$ decay are formed from pairs of oppositely charged tracks having a reconstructed invariant mass within 9 MeV/c^2 (about 3 times the experimental resolution) of the nominal K^0_S mass [24]. The K^0_S candidates are also required to satisfy the criteria described in Ref. [25] to ensure that their decay vertices are displaced from the interaction point (IP). We reconstruct neutral pion candidates from pairs of electromagnetic showers in the ECL that are not matched to any charged track. Showers in the barrel (end-cap) region of the ECL must exceed 60 (100) MeV to be considered as a π^0 daughter candidate. The invariant mass of the π^0 candidate must lie within 25 MeV/c^2 (about 4 times the experimental resolution) of the known π^0 mass [24]. The π^0 momentum is required to be greater than 640 (540) MeV/c for the data sample taken at the $\Upsilon(4S)$ ($\Upsilon(5S)$) resonance.

Reconstructed π^0 and K^0_S candidates are kinematically constrained to the nominal π^0 and K^0_S mass values and combined to form $D^0 \to K^0_S\pi^0$ and $D^0 \to \pi^0\pi^0$ candidates. For the former, we retain the D^0 candidates having an invariant mass in the range $1.750 < M < 1.950$ GeV/c^2, whereas for the latter the range is $1.758 < M < 1.930$ GeV/c^2 in order to suppress background from $D^0 \to K^0_S(\pi^0\pi^0)\pi^0$.

We require π^+_s candidates to originate from near the IP by restricting their impact parameters along and perpendicular to the z axis to be less than 3 and 1 cm, respectively. The z axis is defined to be the direction opposite the e^+ beam. We do not impose any requirement on the number of SVD hits but require that the ratio of PID likelihoods, $\mathcal{L}_\pi/(\mathcal{L}_\pi + \mathcal{L}_K)$, be greater than 0.4. Here, $\mathcal{L}_\pi$

($\mathcal{L}_K$) is the likelihood of a track being a pion (kaon) and is calculated using specific ionization from the CDC, time-of-flight information from the TOF, and the number of photoelectrons in the ACC. With the above PID requirement, the pion identification efficiency is above 95% with a kaon misidentification probability below 5%.

D^{*+} candidates are reconstructed by combining the π_s^+ with a D^0 candidate and requiring that the resultant ΔM value lies in the range [0.14, 0.16] GeV/c^2, where $\Delta M \equiv M(D^{*+}) - M(D^0)$. In order to improve the ΔM resolution, the π_s^+ is constrained to originate from the IP. The sideband used for the selection optimization is $0.15 < \Delta M < 0.16$ GeV/c^2. D mesons produced in B meson decays are rejected by requiring that the D^{*+} candidates have a c.m. momentum greater than 2.5 and 3.1 GeV/c, respectively, for data taken near the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonance. This requirement also significantly reduces combinatorial background.

After applying all selection criteria, we find that about 6% of the total $D^* \to D(\pi^0\pi^0)\pi_s$ events contain multiple candidates, of which about half are due to a misreconstructed π^0 and about half due to a misreconstructed π_s. We select a single D^0 candidate per event by choosing that which has the smallest $\chi^2_{\rm BCS}$. This quantity is defined as

$$\chi^2_{\rm BCS} = \sum \chi^2_{\pi^0} + \left[\frac{M(D^0) - m_{D^0}}{\sigma_M}\right]^2, \qquad (5)$$

where $\chi^2_{\pi^0}$ is the π^0 mass-constrained fit statistic, σ_M is the uncertainty on the reconstructed D mass as determined from MC simulations, and m_{D^0} is the nominal D^0 mass [24]. In case the D^0 candidate is common to more than one D^* candidate, we select the one having the slow pion with the smallest impact parameter perpendicular to the z axis. According to MC simulation, this procedure identifies the correct D^* candidate among multiple candidates about 74% of the time.

Figure 1 shows the ΔM distributions of event candidates in the two decay modes. We describe the signal shapes by the sum of symmetric and asymmetric Gaussian functions with a common mean. The background shapes are modeled with a threshold function as $(x - m_\pi)^\alpha \exp[-\beta(x - m_\pi)]$, where m_π is the nominal charged pion mass [24] and α and β are shape parameters. The asymmetry $A_{\rm rec}$ and the sum of the D^{*+} and D^{*-} yields are obtained from a simultaneous fit to their ΔM distributions. The parameters common in the fit are (for signal) the common mean, the widths of the symmetric and the asymmetric Gaussian functions, and the relative fraction of the two functions, (for background) α and β. The signal yield for $D^0 \to \pi^0\pi^0$ is 34460 ± 273 events and $A_{\rm rec} = (+0.29 \pm 0.64)\%$. For the $D^0 \to K^0_S\pi^0$ case, the signal yield is 466814 ± 773 events and $A_{\rm rec} = (+0.29 \pm 0.15)\%$.

The data samples shown in Fig. 1 are divided into ten bins of $\cos\theta^*$, seven bins of $p_T^{\pi_s}$, and eight bins of $\cos\theta^{\pi_s}$. For each 3D bin, a simultaneous fit analogous to the one

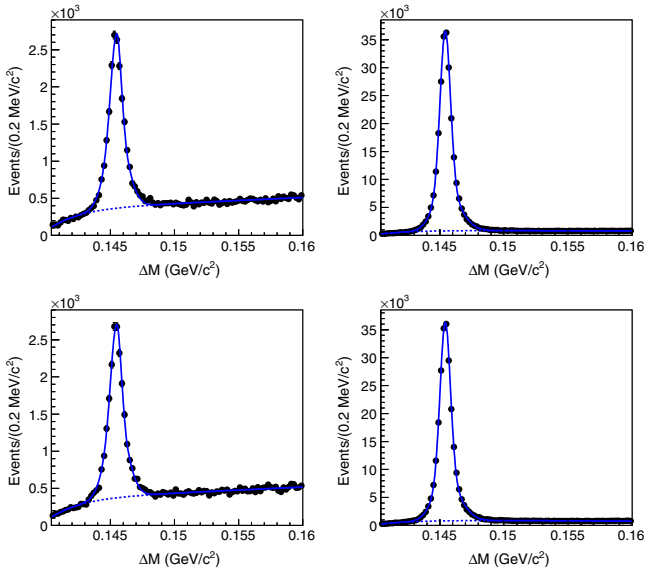

FIG. 1 (color online). Distributions of the mass difference ΔM for the $\pi^0\pi^0$ (left) and $K^0_S\pi^0$ (right) final states. Top (bottom) plots are for the D^{*+} (D^{*-}) sample. Points with error bars are the data, the solid curves show the results of the fit, and the dashed curves are the background predictions.

used for the full sample is performed, and the asymmetry obtained for each bin is corrected by the corresponding $A_\epsilon^{\pi_s}$ obtained in Ref. [17]. Because of limited statistics, the shape for the $D^0 \to \pi^0\pi^0$ signal in a bin of $[p_T^{\pi_s}, \cos\theta^{\pi_s}]$ is taken from the larger $K^0_S\pi^0$ sample. We account for small differences between the two samples using MC simulations. Bins with fewer than 30 events, which correspond to only 2% of the total statistics in the $D^0 \to \pi^0\pi^0$ sample, are removed from the A_{CP} estimation. A weighted average over the $[p_T^{\pi_s}, \cos\theta^{\pi_s}]$ bins having the same $\cos\theta^*$ value is then performed, and A_{CP} and $A_{\rm FB}$ are extracted from Eqs. (3) and (4), respectively. This procedure has been verified with six sets of generic MC samples, each of similar size as the data; the resulting A_{CP} values were found to be in agreement with the generated values. Figure 2 shows A_{CP} and $A_{\rm FB}$ as a function of $|\cos\theta^*|$ obtained for the two data samples. From the weighted average over the $|\cos\theta^*|$ bins, we obtain

$$A_{CP}(\pi^0\pi^0) = (-0.03 \pm 0.64)\%, \qquad (6)$$

$$A_{CP}(K^0_S\pi^0) = (-0.10 \pm 0.16)\%, \qquad (7)$$

where the uncertainties are statistical only, with a reduced χ^2 of 1.7 and 0.7, respectively. The observed $A_{\rm FB}$ values decrease with $|\cos\theta^*|$ as expected but are somewhat lower than the leading-order QED prediction [19]. Higher-order corrections are expected to lower the theoretical prediction, which would bring it into better agreement with our data.

We identify three significant sources of systematic uncertainty (see Table I). The first is due to the uncertainty

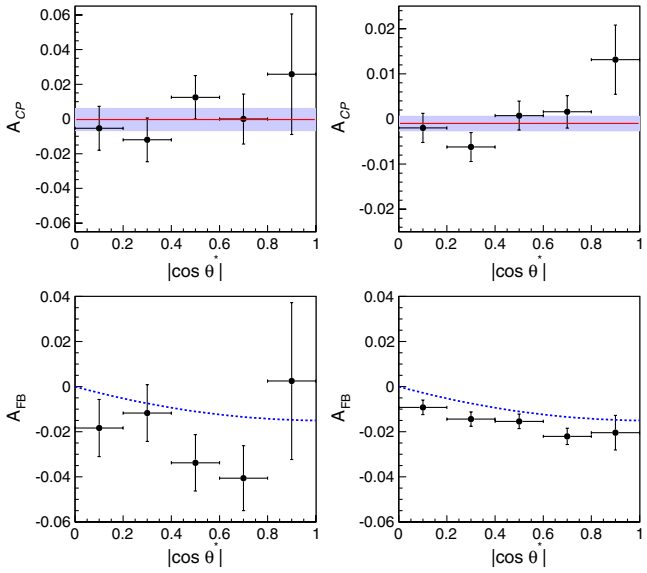

FIG. 2 (color online). CP violation asymmetry A_{CP} (top) and forward-backward asymmetry $A_{\rm FB}$ (bottom) values as a function of $|\cos\theta^*|$. Plots on the left (right) are for the $\pi^0\pi^0$ ($K^0_S\pi^0$) final state. The solid red lines represent the central values obtained from a least-squares minimization, the blue regions for the A_{CP} plots show the 1σ interval, and the dashed blue curves for the $A_{\rm FB}$ plots show the leading-order prediction for $A_{\rm FB}(e^+e^-\to c\bar{c})$.

in the signal shapes, which, in the case of $D^0\to\pi^0\pi^0$, is dominated by the statistics of the calibration mode $D^0\to K^0_S\pi^0$. The second is the slow pion efficiency correction. We estimate its contribution by varying $A_\epsilon^{\pi_s}$ by its statistical error in each of the 7×8 bins of $[p_T^{\pi_s}, \cos\theta^{\pi_s}]$. The third is the A_{CP} extraction procedure itself and is obtained by varying the binning in $|\cos\theta^*|$. For the $D^0\to K^0_S\pi^0$ channel, we correct for a nonvanishing asymmetry originating from the different strong interaction of K^0 and $\bar{K}^0$ mesons with nucleons of the detector material, estimated to be -0.11% in Ref. [26], and assign an additional systematic uncertainty of 0.01%. Finally, we add these individual contributions in quadrature to obtain the total systematic uncertainty. The result is 0.10% (0.07%) for the $\pi^0\pi^0$ ($K^0_S\pi^0$) sample.

In summary, we have measured the time-integrated CP-violating asymmetry A_{CP} in the $D^0\to\pi^0\pi^0$ decay using 966 fb^{-1} of data. After correcting for the detector-induced asymmetries with a precision of 0.07% by using the tagged and untagged $D^0\to K^-\pi^+$ decays, we obtain

TABLE I. Summary of systematic uncertainties (%) in A_{CP}.

Source	$\pi^0\pi^0$	$K^0_S\pi^0$
Signal shape	±0.03	±0.01
Slow pion correction	±0.07	±0.07
A_{CP} extraction method	±0.07	±0.02
$K^0/\bar{K}^0$-material effects	...	±0.01
Total	±0.10	±0.07

$$A_{CP}(D^0\to\pi^0\pi^0) = (-0.03\pm0.64\pm0.10)\%, \quad (8)$$

where the uncertainties are statistical and systematic, respectively. The measured CP asymmetry has an order of magnitude better precision than the previous result [15] and shows no evidence for CP violation. We also measure

$$A_{CP}(D^0\to K^0_S\pi^0) = (-0.21\pm0.16\pm0.07)\%, \quad (9)$$

which supersedes our earlier result [17]. After subtracting CP violation due to K^0-$\bar{K}^0$ mixing, $(-0.339\pm0.007)\%$ [18], the CP asymmetry in $D^0\to\bar{K}^0\pi^0$ decay is found to be $(+0.12\pm0.16\pm0.07)\%$, which is consistent with no CP violation.

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