Evidence for $CP$ Violation in the Decay $D^+ \to K_S^0 \pi^+$

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We observe evidence for CP violation in the decay $D^+ \rightarrow K_S^0\pi^+$ using a data sample with an integrated luminosity of 977 fb$^{-1}$ collected by the Belle detector at the KEKB $e^+e^-$ asymmetric-energy collider. The CP asymmetry in the decay is measured to be $(-0.363 \pm 0.094 \pm 0.067)\%$, which is 3.2 standard deviations away from zero, and is consistent with the expected CP violation due to the neutral kaon in the final state.

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In the standard model (SM), violation of the combined charge-conjugation and parity symmetries (CP) arises from a nonvanishing irreducible phase in the Cabibbo-Kobayashi-Maskawa flavor-mixing matrix [1]. In the SM, CP violation in the charm sector is expected to be very small, $O(0.1\%)$ or below [2]. Since the discovery of the $J/\psi$ [3] and the subsequent discovery of open charm particles [4], CP violation in charmed particle decays has been searched for extensively and only recently became experimentally accessible. To date, after the FOCUS [5], CLEO [6], Belle [7], and BaBar [8] measurements, the world average of the CP asymmetry in the decay $D^+ \rightarrow K_S^0\pi^+$ is $(-0.54 \pm 0.14)\%$, which is the first evidence of CP violation in charmed particles. However, it should be noted that the observed asymmetry is consistent with that expected due to the neutral kaon in the final state and is not ascribed to the charm sector. Recently, LHCb reported $\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$, where $\Delta A_{CP}$ is the CP asymmetry difference between $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays [9]. This is the first evidence of non-zero $\Delta A_{CP}$ in charmed particle decays from a single experiment.

In this Letter we report the first evidence for CP violation in charmed meson decays from a single experiment and in a single decay mode, $D^+ \rightarrow K_S^0\pi^+$, where $K_S^0$ decays to $\pi^+\pi^-$. The CP asymmetry in the decay, $A_{CP}$, is defined as

$$A_{CP}^{D^+\rightarrow K_S^0\pi^+} = \frac{\Gamma(D^+ \rightarrow K_S^0\pi^+)}{\Gamma(D^+ \rightarrow K_S^0\pi^-)} - \frac{\Gamma(D^- \rightarrow K_S^0\pi^-)}{\Gamma(D^- \rightarrow K_S^0\pi^+)} = A_{CP}^{\Delta} + A_{CP}^{\alpha},$$

where $\Gamma$ is the partial decay width, and $A_{CP}^{\Delta}$ and $A_{CP}^{\alpha}$ [10] denote CP asymmetries in the charm decay (DCS) and in $K^0 - \bar{K}^0$ mixing in the SM [11], respectively. The observed $K_S^0\pi^+$ final state is a coherent sum of amplitudes for $D^+ \rightarrow K^0\pi^+$ and $D^+ \rightarrow K^0\pi^+$ decays where the former is Cabibbo-favored (CF) and the latter is doubly Cabibbo-suppressed (DCS). In the absence of direct CP violation in CF and DCS decays (as expected within the SM), the CP asymmetry in $D^+ \rightarrow K_S^0\pi^+$ decay within the SM is $A_{CP}^{\alpha}$, which is measured to be $(-0.332 \pm 0.006)\%$ [12] from $K^0_S$ semileptonic decays [13]. On the other hand, if processes beyond the SM contain additional weak phases other than the one in the Kobayashi-Maskawa ansatz [1], interference between CF
and DCS decays could generate an $\mathcal{O}(1\%)$ direct CP asymmetry in the decay $D^+ \to K_S^0 \pi^+$. Thus, observation of $A_{CP}$ inconsistent with $A_{CP}^{0}$ in $D^+ \to K_S^0 \pi^+$ decay would be strong evidence for processes involving new physics [13, 14].

We determine $A_{GCP}^{D^+ \to K_S^0 \pi^+}$ by measuring the asymmetry in the signal yield

$$A_{rec}^{D^+ \to K_S^0 \pi^+} = \frac{N_{rec}^{D^+ \to K_S^0 \pi^+} - N_{rec}^{D^+ \to K_S^0 \pi^-}}{N_{rec}^{D^+ \to K_S^0 \pi^+} + N_{rec}^{D^+ \to K_S^0 \pi^-}},$$

(2)

where $N_{rec}$ is the number of reconstructed decays. The asymmetry in Eq. (2) includes the forward-backward asymmetry ($A_{FB}$) due to $\gamma^*Z^0$ interference and higher order QED effects in $e^+e^- \to c\bar{c}$ [17], and the detection efficiency asymmetry between $\pi^+$ and $\pi^-$ ($A_{\pi}$) as well as $A_{CP}$. In addition, Ref. [18] calculated another source denoted $A_D$ due to the differences in interactions of $K^0$ and $K^0$ mesons with the material of the detector. (The existence of this effect was pointed out in Ref. [17].) Since we reconstruct the $K_S^0$ with $\pi^+\pi^-$ combinations, the $\pi^+\pi^-$ detection asymmetry cancels out for $K_S^0$. The asymmetry of Eq. (2) can be written as

$$A_{rec}^{D^+ \to K_S^0 \pi^+} = A_{CP}^{D^+ \to K_S^0 \pi^+} + A_{FB}(\cos\theta_{CMS}^{D^+}) + A_{\pi}(p_{lab}^{D^+}, \cos\theta_{\pi^+}) + A_D(p_{K_S^0}^{D^+})$$

(3)

by neglecting the terms involving the product of asymmetries. In Eq. (3), $A_{CP}$ is independent of all kinematic variables other than $K_S^0$ decay time due to the $K_S^0$ in the final state [19]. $A_{FB}$ is an odd function of the cosine of the polar angle of the $D^+$ momentum in the center-of-mass system (CMS), $A_{\pi}$ depends on the transverse momentum and the polar angle of the $\pi^+$ in the laboratory frame (lab), and $A_D$ is a function of the momentum of the $K_S^0$ in the lab. To correct for $A_{\pi}$ in Eq. (3), we use $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^0\pi^0$ decays, and assume the same $A_{FB}$ for $D^+$ and $D^0$ mesons. Since these are CF decays for which the direct CP asymmetry is expected to be negligible, in analogy to Eq. (3), $A_{rec}^{D^+ \to K^-\pi^+\pi^+}$ and $A_{rec}^{D^0 \to K^-\pi^0\pi^0}$ include $A_{FB}$, $A_{K^-}$, and $A_{\pi}$. Thus with the additional $A_{\pi}$ term in $A_{rec}^{D^+ \to K^-\pi^+\pi^+}$, one can measure $A_{\pi}$ by subtracting $A_{rec}^{D^+ \to K^-\pi^+\pi^0}$ from $A_{rec}^{D^+ \to K^-\pi^+\pi^+}$. We obtain $A_{D}$ according to Ref. [18]. Using $A_{rec}^{D^+ \to K_S^0 \pi^+}$ shown in Eq. (4), which is $A_{rec}^{D^+ \to K_S^0 \pi^+}$ after the $A_{\pi}$ and $A_D$ corrections,

$$A_{rec}^{D^+ \to K_S^0 \pi^+_{\text{corr}}} = A_{CP}^{D^+ \to K_S^0 \pi^+} + A_{FB}(\cos\theta_{CMS}^{D^+}),$$

(4)

we extract $A_{CP}$ and $A_{FB}$ using

$$A_{CP}^{D^+ \to K_S^0 \pi^+} = \frac{A_{rec}^{D^+ \to K_S^0 \pi^+_{\text{corr}}} + \cos\theta_{CMS}^{D^+}}{2},$$

(5a)

$$A_{FB}^{D^+} = \frac{A_{rec}^{D^+ \to K_S^0 \pi^+_{\text{corr}}} - \cos\theta_{CMS}^{D^+}}{2},$$

(5b)

Note that extracting $A_{CP}$ in Eq. (4) is crucial in Belle due to the asymmetric detector acceptance in $\cos\theta_{CMS}^{D^+}$.

The data used in this analysis were recorded at the $\Upsilon(nS)$ resonances ($n=1,2,3,4,5$) or near the $\Upsilon(4S)$ resonance with the Belle detector [20] at the $e^+e^-$ asymmetric-energy collider KEKB [21]. The data sample corresponds to an integrated luminosity of 977 fb$^{-1}$.

We apply the same charged track selection criteria that were used in Ref. [22] without requiring associated hits in the silicon vertex detector [23]. We use the standard Belle charged kaon and pion identification [22]. We form $K_S^0$ candidates from $\pi^+\pi^-$ pairs, fitted to a common vertex and requiring the invariant mass of the pair $M(\pi^+\pi^-)$ to be within [0.4820, 0.5126] GeV/$c^2$, regardless of whether the candidate satisfies the standard $K_S^0$ requirements [22]. (We refer to the $K_S^0$ candidates not satisfying the standard criteria as “loose $K_S^{0*}$.”) The $K_S^0$ and $\pi^+$ candidates are combined to form a $D^+$ candidate by fitting them to a common vertex and the $D^+$ candidate is fitted to the $e^+e^-$ interaction point to give the production vertex. To remove combinatorial background as well as $D^+$ mesons, which are produced in possibly CP violating $B$ meson decays, we require the $D^+$ meson momentum calculated in the CMS ($p_{CMS}^+$) to be greater than 2.5 and 3.0 GeV/$c$ for the data taken at the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances, respectively. For the data taken below $\Upsilon(4S)$, which is free of $B$ mesons, we apply the requirement $p_{CMS}^+ > 2.0$ GeV/$c$. In addition to the selections described above, we further optimize the signal sensitivity with four variables: the $\chi^2$ of the $D^+$ decay and production vertex fits ($\chi^2_D$ and $\chi^2_B$), the transverse momentum of the pair ($p_{T\pi^+}$), and the angle between the $D^+$ momentum vector, as reconstructed from the daughters, and the vector joining the $D^+$ production and decay vertices (\$\chi^2_D$). An optimization is performed by maximizing $N_S/\sqrt{N_S+N_B}$ with the four variables varied simultaneously [22], where $N_S+N_B$ are the yields in the $K_S^0\pi^+$ invariant mass signal ([1.855, 1.885] GeV/$c^2$) and sideband ([1.825, 1.840] and [1.900, 1.915] GeV/$c^2$) regions, respectively. The optimal set of ($\chi^2_D$, $\chi^2_B$, $p_{T\pi^+}$, $\xi$) requirements are found to be $<100$, $<10$, $>0.50$ GeV/$c$, $<160\)°), $(<100$, $<10$, $>0.45$ GeV/$c$, $<170\)°), and $(<100$, $<10$, $>0.40$ GeV/$c$, no requirement) for the data taken below the $\Upsilon(4S)$, at the $\Upsilon(4S)$, and at the $\Upsilon(5S)$, respectively. The $D^+$ candidates with the same $K_S^0$ requirement are further optimized with two additional variables which are the $\chi^2$ of the fit of pions from the $K_S^0$ decay and the pion from the
$D^+$ meson decay to a single vertex ($\chi_{3\pi}$), and the angle between the $K_S^0$ momentum vector, as reconstructed from the daughters, and the vector joining the $D^+$ and $K_S^0$ decay vertices ($\zeta$). The two variables are again varied simultaneously and the optimum is found to be $\chi_{3\pi}^2 > 6$ and $\zeta < 4^\circ$ for all data. The inclusion of $D^+$ candidates with the loose $K_S^0$ requirement improves the statistical sensitivity by approximately 5%. After the final selections described above, there remains a background with a broad peaking structure in the $K_S^0\pi^+$ invariant mass signal region, due to misidentification of charged kaons from $D^-\rightarrow K_S^0K^+$ decays. The $D^-\rightarrow \pi^+\pi^-\pi^+$ background is found to be negligible from simulation [28]. Figure 1 shows the distributions of $M(K_S^0\pi^+)$ and $M(K_S^0\pi^-)$ together with the results of the fits described below.

The $D^\pm\rightarrow K_S^0\pi^\pm$ signals are parameterized as a sum of a Gaussian and a bifurcated Gaussian distribution with a common mean. The combinatorial background is parameterized with the form $e^{\alpha + \beta M(K_S^0\pi^\pm)}$, where $\alpha$ and $\beta$ are free parameters. The shapes and normalizations of the $D^\pm\rightarrow K_S^0K^\pm$ misidentification backgrounds are obtained with taking the asymmetry in $D^\pm\rightarrow K_S^0K^\pm$ into account as described in Refs. [7, 22]. Both the shapes and the normalizations of the misidentification backgrounds are fixed in the fit. The asymmetry and the sum of the $D^+$ and $D^−$ yields are directly obtained from a simultaneous fit to the $D^+$ and $D^−$ candidate distributions. Besides the asymmetry and the total signal yield, the common parameters in the simultaneous fit are the widths of the Gaussian and the bifurcated Gaussian and the ratio of their amplitudes. The asymmetry and the sum of the $D^+$ and $D^−$ yields from the fit are $(-0.146\pm0.094)%$ and $(1738\pm2)\times10^3$, respectively, where the errors are statistical.
becomes $A^+_{CP}$, where $\pi^+$ refers to the $\pi^+$ with higher $p_T$ in the decay. The detector asymmetry, $A^+_{\pi^+}$, is measured from simultaneous fits to the weighted $M(K^{\mp}p^{\mp}p^{\pm})$ distributions in 10×10 bins of the 2D phase space ($p_T^{\pi^+}$, $\cos\theta^{\pi^+}$) with the same parameterization used in $D^0 \rightarrow K^-\pi^+\pi^0$ decays. Figure 2 shows the measured $A^+_{\pi^+}$ in bins of $p_T^{\pi^+}$ and $\cos\theta^{\pi^+}$ together with $A_{rec}^{D^+\rightarrow K^-\pi^+\pi^+}$ for comparison. The average of $A^+_{\pi^+}$ over phase space is $(+0.078 \pm 0.040)\%$, where the error is statistical.

Based on a recent study of the $A_{D^-}$ [18], we obtain the asymmetry in bins of $K^0_S$ momentum in the lab. For the present analysis, $A_{D^-}$ is approximately 0.1% after integrating over the phase space of the two-body decay [18].

The data samples shown in Fig. 4 are divided into 10×10×16 bins of the 3D phase space ($p_T^{\pi^+}$, $\cos\theta^{\pi^+}$, $p_T^{K^0_S}$). Each $D^\pm \rightarrow K^0_S\pi^\pm$ candidate is then weighted with a factor of $(1 \mp A^-_{\pi^+})(1 \mp A_{D^-})$ in the 3D phase space. The weighted $M(K^0_S\pi^\pm)$ distributions in bins of $\cos\theta_{D^-}^{CMS}$ are fitted simultaneously to obtain the corrected asymmetry. We fit the linear component in $\cos\theta_{D^-}^{CMS}$ to determine $A_{FB}$ while the $A_{CP}$ component is uniform in $\cos\theta_{D^-}^{CMS}$. Figure 3 shows $A_{CP}^{D^+\rightarrow K^0_S\pi^+}$ and $A_{FB}$ as a function of $|\cos\theta_{D^-}^{CMS}|$. From a weighted average over the $|\cos\theta_{D^-}^{CMS}|$ bins, we obtain $A_{CP}^{D^+\rightarrow K^0_S\pi^+} = (-0.363 \pm 0.094)\%$, where the error is statistical. Without the $A_D$ correction as in previous publications [2][8], the value of $A_{CP}$ is $(-0.462 \pm 0.094)\%$.

The method is validated with fully simulated Monte Carlo events [24] and the result is consistent with no input asymmetry. We also consider other sources of systematic uncertainty. The dominant one in the $A_{CP}$ measurement is the $A^+_{CP}$ determination, the uncertainty of which is mainly due to the statistical uncertainties in the $D^+ \rightarrow K^-\pi^+\pi^+$ and $D^0 \rightarrow K^-\pi^+\pi^0$ samples. These are found to be 0.040% and 0.048%, respectively, from a simplified simulation study. A possible $A_{CP}$ in the $D^0 \rightarrow K^-\pi^+\pi^0$ final state is estimated with the relation, $A_{CP} = -y\sin\delta\sin\phi\sqrt{R}$ [27]. Using the 95% upper and lower limits on $D^0 - D^\bar{0}$ mixing and $CP$ violation parameters [28], $A_{CP}$ in the $D^0 \rightarrow K^-\pi^+\pi^0$ final state is estimated to be less than 0.014% and this is included as one of systematic uncertainties in the $A^+_{CP}$ determination. By adding the contributions in quadrature, the systematic uncertainty in the $A^+_{CP}$ determination is estimated to be 0.064%. We estimate 0.003% and 0.008% systematic uncertainties due to the choice of the fitting method and that of the $\cos\theta_{D^-}^{CMS}$ binning, respectively. Finally, we add the systematic uncertainty in the $A_{D^-}$ correction, which is 0.016% based on Ref. [18]. The quadratic sum of the above uncertainties, 0.067%, is taken as the total systematic uncertainty.

We find $A_{CP}^{D^+\rightarrow K^0_S\pi^+} = (-0.363 \pm 0.094 \pm 0.067)\%$. This measurement supersedes our previous determination of $A_{CP}^{D^+\rightarrow K^0_S\pi^+}$ [24]. In Table I we compare all the available measurements and give the new world average.

### TABLE I: Summary of $A_{CP}^{D^+\rightarrow K^0_S\pi^+}$ measurements (where the first uncertainties are statistical and the second systematic), together with their average (where only the total uncertainty is quoted).

| Experiment | $A_{CP}^{D^+\rightarrow K^0_S\pi^+}$ (%) |
|------------|---------------------------------|
| FOCUS [9]  | $-1.6 \pm 1.5 \pm 0.9$          |
| CLEO [6]   | $-1.3 \pm 0.7 \pm 0.3$          |
| BaBar [8]  | $-0.44 \pm 0.13 \pm 0.10$      |
| Belle (this measurement) | $-0.363 \pm 0.094 \pm 0.067$ |
| New world average | $-0.41 \pm 0.09$               |

According to Grossman and Nir [19], we can estimate the experimentally measured $CP$ asymmetry induced by SM $K^0 - \bar{K}^0$ mixing, $A_{CP}^{K^0}$, assuming negligible DCS decay $D^+ \rightarrow K^0\pi^+$ in the final state $D^+ \rightarrow K^0_S\pi^+$. By multiplying $A_{CP}^{K^0}$ by the correction factor 1.022 ± 0.007 due to the acceptance effects as a function of $K^0_S$ decay time in our detector, we find the measured asymmetry due to the neutral kaons to be $(-0.339 \pm 0.007)\%$.

In summary, we report evidence for $CP$ violation in the decay $D^+ \rightarrow K^0_S\pi^+$ using a data sample corresponding to an integrated luminosity of 977 fb$^{-1}$ collected with the Belle detector. The $CP$ asymmetry in the decay is measured to be $(-0.363 \pm 0.094 \pm 0.067)\%$, which represents the first evidence for $CP$ violation in charmed meson decays from a single experiment and a single decay mode. After subtracting the contribution due to $K^0 - \bar{K}^0$ mixing ($A_{CP}^{K^0}$), the $CP$ asymmetry due to the change of charm ($A_{CP}^{charm} = A_{CP}^{D^+\rightarrow K^0_S\pi^+}$) is consistent with zero.
\[ A_{CP}^{K_0} = (-0.024 \pm 0.094 \pm 0.067)\% \]. The measurement in the decay \( D^+ \to K_S^0 \pi^+ \) is the most precise measurement of \( A_{CP} \) in charm decays to date and can be used to place stringent constraints on new physics models in the charm sector [13, 16].

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Throughout this Letter the charge-conjugate decay modes are implied unless stated otherwise. [17] H. J. Lipkin and Z.-Z. Xing, Phys. Lett. B 450, 405 (1999); G. D’Ambrosio and D.-N. Gao, Phys. Lett. B 513, 123 (2001).

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