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Phys. Rev. Lett. **109**, 021601 — Published 11 July 2012

DOI: 10.1103/PhysRevLett.109.021601

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We observe evidence for CP violation in the decay $D^+ \to K^0_S\pi^+$ 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.

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

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, $\mathcal{O}(0.1\%)$ or below [2]. Since the discovery of the J/ψ [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 $D^+ \to K^0_S\pi^+$ [9] is $(-0.54\pm0.14)\%$, 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 $\Delta A_{CP} = (-0.82\pm0.21\pm0.11)\%$, where ΔA_{CP} is the CP asymmetry difference between $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays [10]. This is the first evidence of non-zero ΔA_{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, $D^+ \to K^0_S\pi^+$, where K^0_S decays to $\pi^+\pi^-$. The CP asymmetry in the decay, A_{CP}, is defined as

$$\begin{aligned} A_{CP}^{D^+\to K^0_S\pi^+} &\equiv \frac{\Gamma(D^+ \to K^0_S\pi^+) - \Gamma(D^- \to K^0_S\pi^-)}{\Gamma(D^+ \to K^0_S\pi^+) + \Gamma(D^- \to K^0_S\pi^-)} \\ &= A_{CP}^{\Delta C} + A_{CP}^{\bar{K}^0}, \end{aligned} \quad (1)$$

where Γ is the partial decay width, $A_{CP}^{\Delta C}$ and $A_{CP}^{\bar{K}^0}$ [11] denote CP asymmetries in the charm decay (ΔC) and the asymmetry due to $K^0 - \bar{K}^0$ mixing in the SM [12, 13], respectively. The observed $K^0_S\pi^+$ final state is a coherent sum of amplitudes for $D^+ \to \bar{K}^0\pi^+$ and $D^+ \to K^0\pi^+$ 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 $D^+ \to K^0_S\pi^+$ decay within the SM is $A_{CP}^{\bar{K}^0}$, which is measured to be $(-0.332\pm0.006)\%$ [14] from K^0_L semileptonic decays [15]. 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 $D^+ \to K^0_S\pi^+$ [13]. Thus, observation of A_{CP} inconsistent with $A^{\bar{K}^0}_{CP}$ in $D^+ \to K^0_S\pi^+$ decay would be strong evidence for processes involving new physics [13, 16].

We determine $A^{D^+\to K^0_S\pi^+}_{CP}$ by measuring the asymmetry in the signal yield

$$A^{D^+\to K^0_S\pi^+}_{\rm rec} = \frac{N^{D^+\to K^0_S\pi^+}_{\rm rec} - N^{D^-\to K^0_S\pi^-}_{\rm rec}}{N^{D^+\to K^0_S\pi^+}_{\rm rec} + N^{D^-\to K^0_S\pi^-}_{\rm rec}}, \quad (2)$$

where $N_{\rm rec}$ is the number of reconstructed decays. The asymmetry in Eq. (2) includes the forward-backward asymmetry (A_{FB}) due to γ^*-Z^0 interference and higher order QED effects in $e^+e^- \to c\bar{c}$ [17], and the detection efficiency asymmetry between π^+ and π^- ($A^{\pi^+}_\epsilon$) as well as A_{CP}. In addition, Ref. [18] calculated another source of $A_{\mathcal{D}}$ due to the differences in interactions of $\bar{K}^0$ and K^0 mesons with the material of the detector (the existence of this effect was pointed out in Ref. [7]). Since we reconstruct the K^0_S with $\pi^+\pi^-$ combinations, the $\pi^+\pi^-$ detection asymmetry cancels out for K^0_S. The asymmetry of Eq. (2) can be written as

$$\begin{aligned} A^{D^+\to K^0_S\pi^+}_{\rm rec} &= A^{D^+\to K^0_S\pi^+}_{CP} + A^{D^+}_{FB}(\cos\theta^{\rm CMS}_{D^+}) \\ &+ A^{\pi^+}_\epsilon(p^{\rm lab}_{T\pi^+}, \cos\theta^{\rm lab}_{\pi^+}) + A_{\mathcal{D}}(p^{\rm lab}_{K^0_S}) \quad (3) \end{aligned}$$

by neglecting the terms involving the product of asymmetries. In Eq. (3) A_{CP} is independent of all kinematic variables other than K^0_S decay time due to the K^0_S in the final state [19], $A^{D^+}_{FB}$ is an odd function of the cosine of the polar angle of the D^+ momentum in the center-of-mass system (CMS), $A^{\pi^+}_\epsilon$ depends on the transverse momentum and the polar angle of the π^+ in the laboratory frame (lab), and $A_{\mathcal{D}}$ is a function of the momentum of the K^0_S in the lab. To correct for $A^{\pi^+}_\epsilon$ in Eq. (3) we use $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+\pi^0$ 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), $A^{D^+\to K^-\pi^+\pi^+}_{\rm rec}$ and $A^{D^0\to K^-\pi^+\pi^0}_{\rm rec}$ include A_{FB}, $A^{K^-}_\epsilon$, and $A^{\pi^+}_\epsilon$. Thus with the additional $A^{\pi^+}_\epsilon$ term in $A^{D^+\to K^-\pi^+\pi^+}_{\rm rec}$, one can measure $A^{\pi^+}_\epsilon$ by subtracting $A^{D^0\to K^-\pi^+\pi^0}_{\rm rec}$ from $A^{D^+\to K^-\pi^+\pi^+}_{\rm rec}$. We obtain $A_{\mathcal{D}}$ according to Ref. [18]. Using $A^{D^+\to K^0_S\pi^+_{\rm corr}}_{\rm rec}$ shown in Eq. (4), which is $A^{D^+\to K^0_S\pi^+}_{\rm rec}$ after the $A^{\pi^+}_\epsilon$ and $A_{\mathcal{D}}$ corrections,

$$A^{D^+\to K^0_S\pi^+_{\rm corr}}_{\rm rec} = A^{D^+\to K^0_S\pi^+}_{CP} + A^{D^+}_{FB}(\cos\theta^{\rm CMS}_{D^+}), \quad (4)$$

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

$$\begin{aligned} A^{D^+\to K^0_S\pi^+}_{CP} &= [A^{D^+\to K^0_S\pi^+_{\rm corr}}_{\rm rec}(+\cos\theta^{\rm CMS}_{D^+}) \\ &+ A^{D^+\to K^0_S\pi^+_{\rm corr}}_{\rm rec}(-\cos\theta^{\rm CMS}_{D^+})]/2, \quad (5a) \\ A^{D^+}_{FB} &= [A^{D^+\to K^0_S\pi^+_{\rm corr}}_{\rm rec}(+\cos\theta^{\rm CMS}_{D^+}) \\ &- A^{D^+\to K^0_S\pi^+_{\rm corr}}_{\rm rec}(-\cos\theta^{\rm CMS}_{D^+})]/2. \quad (5b) \end{aligned}$$

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

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^0_S candidates from $\pi^+\pi^-$ pairs, fitted to a common vertex and requiring the invariant mass of the pair $M(\pi^+\pi^-)$ to be within $[0.4826, 0.5126]$ GeV/c^2, regardless of whether the candidate satisfies the standard K^0_S requirements [22] (we refer to the K^0_S candidates not satisfying the standard criteria as "loose K^0_S"). The K^0_S and π^+ 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 ($p^*_{D^+}$) 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 $p^*_{D^+}>2.0$ GeV/c. In addition to the selections described above, we further optimize the signal sensitivity with four variables: the χ^2 of the D^+ decay and production vertex fits (χ^2_D and χ^2_P), the transverse momentum of the π^+ ($p_{T\pi^+}$), and the angle between the D^+ momentum vector, as reconstructed from the daughters, and the vector joining the D^+ production and decay vertices (ξ) [24]. An optimization is performed by maximizing $\mathcal{N}_S/\sqrt{\mathcal{N}_S+\mathcal{N}_B}$ with the four variables varied simultaneously [25], where $\mathcal{N}_S+\mathcal{N}_B$ and $\mathcal{N}_B$ are the yields in the $K^0_S\pi^+$ 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 (χ^2_D, χ^2_P, $p_{T\pi^+}$, ξ) 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 loose K^0_S requirement are further optimized with two additional variables which are the χ^2 of the fit of pions from the K^0_S decay and the pion from the D^+ meson decay to a single vertex ($\chi^2_{3\pi}$), 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 (ζ). The two variables are again varied simultaneously and the optimum is found to be $\chi^2_{3\pi}>6$ 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 $D_s^+ \to K_S^0 K^+$ decays. The $D^+ \to \pi^+\pi^-\pi^+$ background is found to be negligible from simulation [26]. 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.

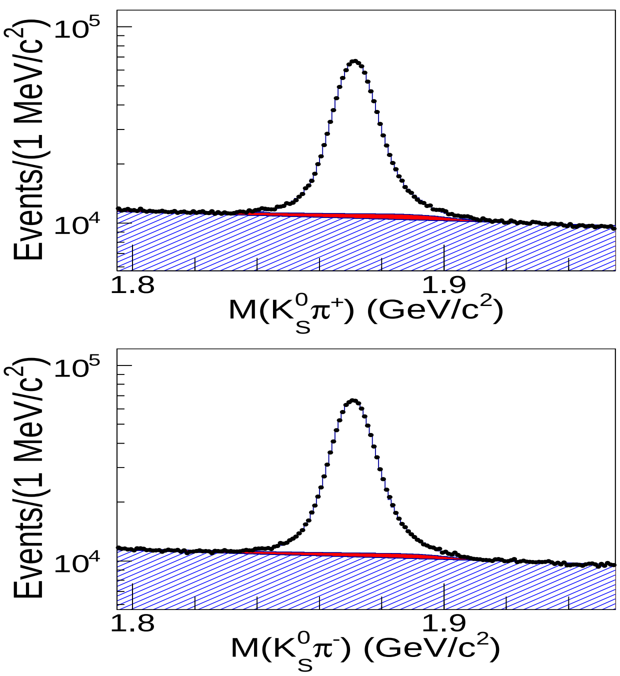

FIG. 1: Distributions of $M(K_S^0\pi^+)$ (top) and $M(K_S^0\pi^-)$ (bottom). Dots with error bars are the data while the histograms show the results of the parameterizations of the data. Open histograms represent the $D^\pm \to K_S^0\pi^\pm$ signal. Shaded and hatched regions are $D_s^\pm \to K_S^0 K^\pm$ misidentification and combinatorial backgrounds, respectively.

The $D^\pm \to K_S^0\pi^\pm$ 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 α and β are free parameters. The shapes and normalizations of the $D_s^\pm \to K_S^0 K^\pm$ misidentification backgrounds are obtained with taking the asymmetry in $D_s^\pm \to K_S^0 K^\pm$ 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.

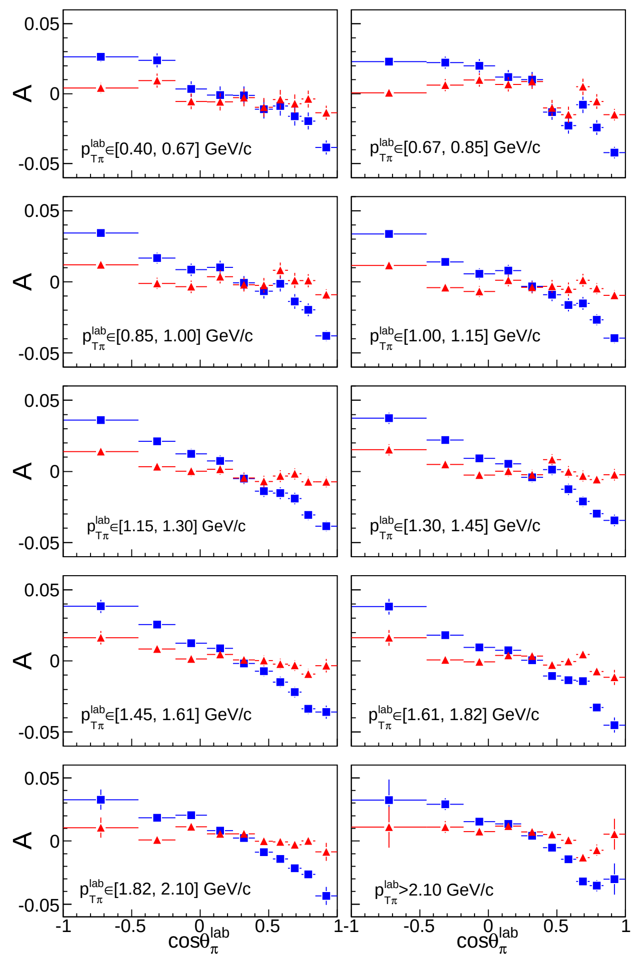

FIG. 2: $A_\epsilon^{\pi^+}$ map in bins of $p_T^{\rm lab}$ and $\cos\theta^{\rm lab}$ of the π^+ obtained with the $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+\pi^0$ samples (triangles). The $A_{\rm rec}^{D^+\to K^-\pi^+\pi^+}$ map is also shown (rectangles).

To obtain $A_\epsilon^{\pi^+}$ we first extract $A_{\rm rec}^{D^0\to K^-\pi^+\pi^0}$ from a simultaneous fit with the same parameterizations for the signal except for the misidentification background. The values of $A_{\rm rec}^{D^0\to K^-\pi^+\pi^0}$ are evaluated in $4\times4\times4\times4\times4$ bins of the five-dimensional (5D) phase space ($p_{TK^-}^{\rm lab}$, $\cos\theta_{K^-}^{\rm lab}$, $p_{T\pi^+}^{\rm lab}$, $\cos\theta_{\pi^+}^{\rm lab}$, $\cos\theta_{D^0}^{\rm CMS}$). Each $D^\pm \to K^\mp\pi^\pm\pi^\pm$ candidate is then weighted with a factor of $1\mp A_{\rm rec}^{D^0\to K^-\pi^+\pi^0}$ in the corresponding bin of the 5D phase space, where the phase space of the $\pi^\pm$ with lower p_T in $D^\pm \to K^\mp\pi^\pm\pi^\pm$ decay is used. After this weighting, the asymmetry in $D^+ \to K^-\pi^+\pi^+$ decay sample becomes $A_\epsilon^{\pi^+}$, where π^+ refers to the π^+ with higher p_T

in the decay. The detector asymmetry, $A_\epsilon^{\pi^+}$, is measured from simultaneous fits to the weighted $M(K^\mp\pi^\pm\pi^\pm)$ distributions in 10×10 bins of the 2D phase space ($p_{T\pi^+}^{\rm lab}$, $\cos\theta_{\pi^+}^{\rm lab}$) with the same parameterization used in $D^0 \to K^-\pi^+\pi^0$ decays. Figure 2 shows the measured $A_\epsilon^{\pi^+}$ in bins of $p_{T\pi^+}^{\rm lab}$ and $\cos\theta_{\pi^+}^{\rm lab}$ together with $A_{\rm rec}^{D^+\to K^-\pi^+\pi^+}$ for comparison. The average of $A_\epsilon^{\pi^+}$ over phase space is $(+0.078 \pm 0.040)\%$, where the error is statistical.

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

The data samples shown in Fig. 1 are divided into 10×10×16 bins of the 3D phase space ($p_{T\pi^+}^{\rm lab}$, $\cos\theta_{\pi^+}^{\rm lab}$, $p_{K_S^0}^{\rm lab}$). Each $D^\pm \to K_S^0\pi^\pm$ candidate is then weighted with a factor of $(1 \mp A_\epsilon^{\pi^+})(1 \mp A_\mathcal{D})$ in the 3D phase space. The weighted $M(K_S^0\pi^\pm)$ distributions in bins of $\cos\theta_{D^+}^{\rm CMS}$ are fitted simultaneously to obtain the corrected asymmetry. We fit the linear component in $\cos\theta_{D^+}^{\rm CMS}$ to determine A_{FB} while the A_{CP} component is uniform in $\cos\theta_{D^+}^{\rm CMS}$. Figure 3 shows $A_{CP}^{D^+\to K_S^0\pi^+}$ and $A_{FB}^{D^+}$ as a function of $|\cos\theta_{D^+}^{\rm CMS}|$. From a weighted average over the $|\cos\theta_{D^+}^{\rm CMS}|$ bins, we obtain $A_{CP}^{D^+\to K_S^0\pi^+} = (-0.363 \pm 0.094)\%$, where the error is statistical. Without the $A_\mathcal{D}$ correction as in previous publications [5–8], the value of A_{CP} is $(-0.462 \pm 0.094)\%$.

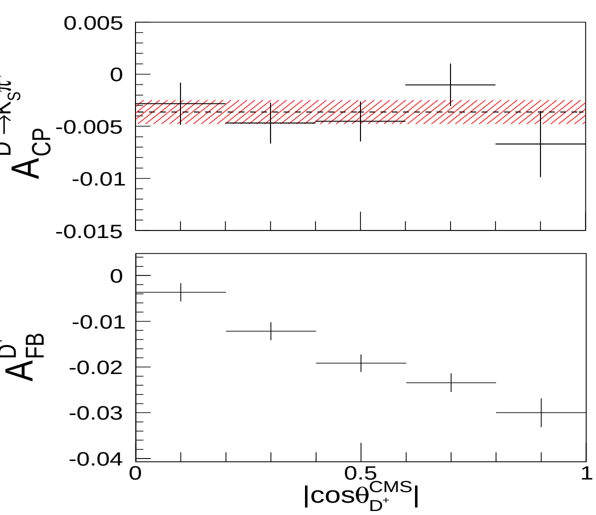

FIG. 3: Measured A_{CP} (top) and A_{FB} (bottom) values as a function of $|\cos\theta_{D^+}^{\rm CMS}|$. In the top plot, the dashed line is the mean value of A_{CP} while the hatched band is the $\pm1\sigma_{\rm total}$ interval, where $\sigma_{\rm total}$ is the total uncertainty.

The method is validated with fully simulated Monte Carlo events [26] 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 $A_\epsilon^{\pi^+}$ determination, the uncertainty of which is mainly due to the statistical uncertainties in the $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+\pi^0$ samples. These are found to be 0.040% and 0.048%, respectively, from a simplified simulation study. A possible A_{CP} in the $D^0 \to K^-\pi^+\pi^0$ 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 $D^0-\bar{D}^0$ mixing and CP violation parameters [28], A_{CP} in the $D^0 \to K^-\pi^+\pi^0$ final state is estimated to be less than 0.014% and this is included as one of systematic uncertainties in the $A_\epsilon^{\pi^+}$ determination. By adding the contributions in quadrature, the systematic uncertainty in the $A_\epsilon^{\pi^+}$ 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 $\cos\theta_{D^+}^{\rm CMS}$ binning, respectively. Finally, we add the systematic uncertainty in the $A_\mathcal{D}$ 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 $A_{CP}^{D^+\to K_S^0\pi^+} = (-0.363\pm0.094\pm0.067)\%$. This measurement supersedes our previous determination of $A_{CP}^{D^+\to K_S^0\pi^+}$ [7]. In Table I, we compare all the available measurements and give the new world average.

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

Experiment	$A_{CP}^{D^+\to K_S^0\pi^+}$ (%)
FOCUS [5]	$-1.6\pm1.5\pm0.9$
CLEO [6]	$-1.3\pm0.7\pm0.3$
BaBar [8]	$-0.44\pm0.13\pm0.10$
Belle (this measurement)	$-0.363\pm0.094\pm0.067$
New world average	-0.41 ± 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, $A_{CP}^{\bar{K}^0}$, assuming negligible DCS decay $D^+ \to K^0\pi^+$ in the final state $D^+ \to K_S^0\pi^+$. By multiplying $A_{CP}^{\bar{K}^0}$ by the correction factor 1.040 ± 0.005 due to the acceptance effects as a function of K_S^0 decay time in our detector, we find the the measured asymmetry due to the neutral kaons to be $(-0.345 \pm 0.008)\%$.

In summary, we report evidence for CP violation in the decay $D^+ \to K_S^0\pi^+$ 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 ($A_{CP}^{\bar{K}^0}$), the CP asymmetry due to the change of charm ($A_{CP}^{\Delta C} = A_{CP}^{D^+\to\bar{K}^0\pi^+}$) is consistent with zero, $A_{CP}^{\Delta C} = (-0.018 \pm 0.094 \pm 0.068)\%$. The measurement in the decay $D^+ \to K^0_S\pi^+$ 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].

We thank the KEKB group for excellent operation of the accelerator; the KEK cryogenics group for efficient solenoid operations; and the KEK computer group, the NII, and PNNL/EMSL for valuable computing and SINET4 network support. We acknowledge support from MEXT, JSPS and Nagoya's TLPRC (Japan); ARC and DIISR (Australia); NSFC (China); MSMT (Czechia); DST (India); INFN (Italy); MEST, NRF, GSDC of KISTI, and WCU (Korea); MNiSW (Poland); MES and RFAAE (Russia); ARRS (Slovenia); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE and NSF (USA). B. R. Ko acknowledges support by a Korea University Grant, NRF Grant No. 2011-0025750, and E. Won by NRF Grant No. 2011-0030865.

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