Search for CP Violation in the Decays $D_{(s)}^+ \to K_S^0 \pi^+$ and $D_{(s)}^+ \to K_S^0 K^+$

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We have searched for CP violation in the charmed meson decays $D^+_{(s)} \to K^0_S\pi^+$ and $D^+_{(s)} \to K^0_S K^+$ using 673 fb^{-1} of data collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. No evidence for CP violation is observed. We report the most sensitive CP asymmetry measurements to date for these decays: $A_{CP}^{D^+\to K^0_S\pi^+} = (-0.71 \pm 0.19 \pm 0.20)\%$, $A_{CP}^{D^+_s\to K^0_S\pi^+} = (+5.45 \pm 2.50 \pm 0.33)\%$, $A_{CP}^{D^+\to K^0_S K^+} = (-0.16 \pm 0.58 \pm 0.25)\%$, and $A_{CP}^{D^+_s\to K^0_S K^+} = (+0.12 \pm 0.36 \pm 0.22)\%$, where the first uncertainties are statistical and the second are systematic.

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Violation of the combined charge-conjugation and parity symmetries (CP) in the standard model (SM) is produced by a nonvanishing phase in the Cabibbo-Kobayashi-Maskawa flavor-mixing matrix [1]. For charged meson decays this may be observed as a nonzero CP asymmetry, defined as

$$A_{CP} = \frac{\Gamma(X^+ \to f^+) - \Gamma(X^- \to f^-)}{\Gamma(X^+ \to f^+) + \Gamma(X^- \to f^-)}, \tag{1}$$

where Γ is the partial decay width, X denotes a charged meson, and f is a final state.

In the SM, the charmed particle processes for which a significant nonvanishing CP violation is expected are singly Cabibbo-suppressed (SCS) decays in which there is both interference between two different decay amplitudes and a strong phase shift from final state interactions. In the SM, CP violation in SCS charmed meson decays is predicted to occur at the level of $\mathcal{O}(0.1)\%$ or lower [2]. The SM also predicts a CP asymmetry in the final states containing a neutral kaon that is produced via $K^0 - \bar{K}^0$ mixing even if no CP violating phase exists in the charm decay amplitudes. The expected magnitude for this type of asymmetry is $(0.332 \pm 0.006)\%$ from K^0_L semileptonic decay [3]. Searches for CP violation in charmed mesons are complementary to those in B and K mesons, since the former tests the CP violating couplings of the up-type quarks while the latter those of the down-type quarks.

In this Letter we report results from searches for CP violation in the $D^+_s \to K^0_S\pi^+$, $D^+ \to K^0_S K^+$, $D^+ \to K^0_S\pi^+$, and $D^+_s \to K^0_S K^+$ decay processes [4]. The former two channels are SCS decays and the latter two are mixtures of Cabibbo-favored (CF) and doubly Cabibbo-suppressed (DCS) decays, where SM CP violations described above are expected. Observing A_{CP} values of $\mathcal{O}(1)\%$ or larger in the decays considered in this Letter would represent strong evidence for processes involving physics beyond the SM [5].

The data used in this analysis were recorded at or near the $\Upsilon(4S)$ resonance with the Belle detector [6] at the e^+e^- asymmetric-energy collider KEKB [7]. The sample corresponds to an integrated luminosity of 673 fb^{-1}.

D^+ and D^+_s candidates are reconstructed using the same requirements used in the measurement of the branching ratios for these same decays reported in Ref. [8]. Figure 1 shows the reconstructed $K^0_S\pi^\pm$ and $K^0_S K^\pm$ invariant mass distributions. All signals are parametrized as a sum of two Gaussian distributions except for $D^+_s \to K^0_S\pi^+$ in which a single Gaussian is used for the signal parametrization. The parametrizations of the random combinatorial background and the peaking background due to K/π misidentification are described in detail in Ref. [8].

We determine the quantities $A_{CP}^{X^+\to K^0_S h^+}$ defined in Eq. (1) by measuring the signal yield asymmetry

$$A_{\rm rec}^{X^+\to K^0_S h^+} = \frac{N_{\rm rec}^{X^+\to K^0_S h^+} - N_{\rm rec}^{X^-\to K^0_S h^-}}{N_{\rm rec}^{X^+\to K^0_S h^+} + N_{\rm rec}^{X^-\to K^0_S h^-}}, \tag{2}$$

where $N_{\rm rec}$ is the number of reconstructed decays and h is a charged hadron. The measured asymmetry in Eq. (2) includes two contributions other than A_{CP}. One is the forward-backward asymmetry ($A_{\rm FB}$) due to $\gamma^* - Z^0$ interference in $e^+e^- \to c\bar{c}$ and the other is a detection efficiency asymmetry between positively and negatively charged tracks ($A_\epsilon^{h^+}$). Since K^0_S mesons are reconstructed from a $\pi^+\pi^-$ pair, there is no detection asymmetry other than $A_\epsilon^{h^+}$. Equation (2) can therefore be expressed as

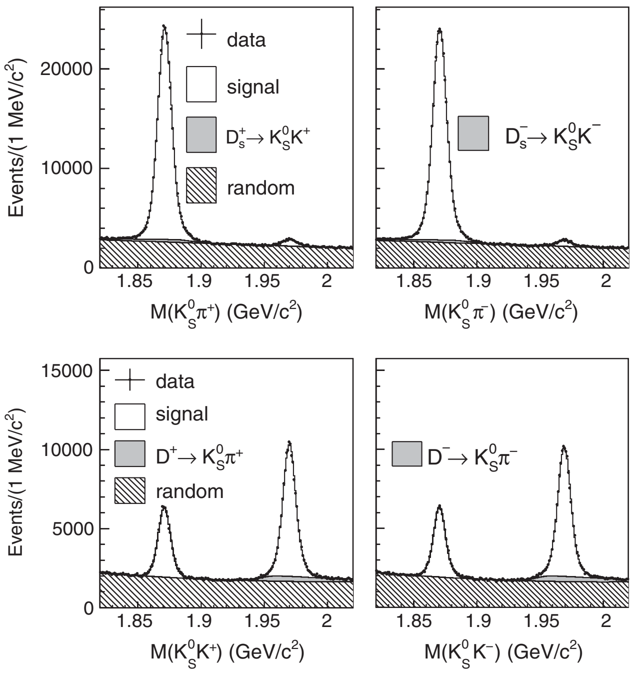

FIG. 1. Invariant mass distributions for the $K_S^0\pi^\pm$ and $K_S^0K^\pm$ final states. Points with error bars (note the small size of them due to the large sample) show the data and the histograms show the results of the parametrizations of the data. Signal, peaking background, and random combinatorial background components are also shown.

$$A_{\rm rec}^{X^+\to K_S^0 h^+} = A_{CP}^{X^+\to K_S^0 h^+} + A_{\rm FB}^{X^+} + A_\epsilon^{h^+}. \qquad (3)$$

To correct for the asymmetries other than A_{CP}, we use reconstructed samples of $D_s^+ \to \phi\pi^+$ and $D^0 \to K^-\pi^+$ decays and assume that A_{CP} in CF decays is negligibly small at the current experimental sensitivity and that $A_{\rm FB}$ is the same for all charmed mesons. We reconstruct ϕ mesons via their K^+K^- decay channel for $D_s^+ \to \phi\pi^+$, requiring the K^+K^- invariant mass to be between 1.01 and 1.03 GeV$/c^2$.

The measured asymmetry for $D_s^+ \to \phi\pi^+$ is the sum of $A_{\rm FB}^{D_s^+}$ and $A_\epsilon^{\pi^+}$. Hence one can extract the A_{CP} value for the $K_S^0\pi^+$ final states by subtracting the measured asymmetry for $D_s^+ \to \phi\pi^+$ from that for $D_{(s)}^+ \to K_S^0\pi^+$. The subtraction is performed in bins of π^+ momentum, $p_\pi^{\rm lab}$, and polar angle in the laboratory system, $\cos\theta_\pi^{\rm lab}$ (because $A_\epsilon^{h^+}$ depends on these two variables while it is uniform in azimuthal angle), and the charmed meson's polar angle in the center-of-mass system, $\cos\theta_{D_{(s)}^+}^{\rm CMS}$ (since $\cos\theta_{D_{(s)}^+}^{\rm CMS}$ is correlated with $\cos\theta_\pi^{\rm lab}$ and $A_{\rm FB}^{D_{(s)}^+}$ depends on it). The choice of the three-dimensional (3D) binning is selected in order to avoid large statistical fluctuations in each bin. Figure 2 shows the A_{CP} map of $D^+ \to K_S^0\pi^+$ in bins of ($p_\pi^{\rm lab}$, $\cos\theta_\pi^{\rm lab}$, $\cos\theta_{D_{(s)}^+}^{\rm CMS}$). Calculating a weighted average of the A_{CP} values over the 3D bins, we obtain $A_{CP}^{D^+\to K_S^0\pi^+} = (-0.71 \pm 0.26)\%$ where the uncertainty originates from the finite size of the $D^+ \to K_S^0\pi^+$ (0.19%) and $D_s^+ \to \phi\pi^+$ (0.18%) samples. The $\chi^2/$d.o.f over the 3D bins is found to be $31.4/24$ which corresponds to 14% probability.

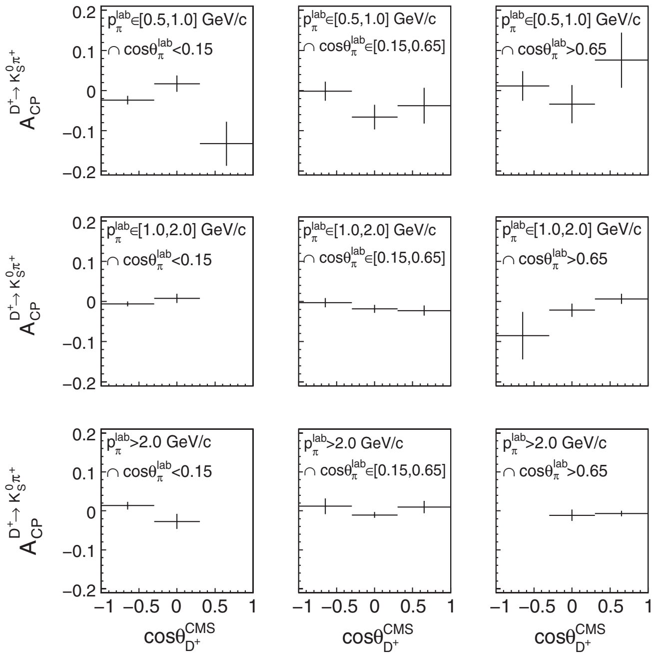

FIG. 2. Measured A_{CP} values for $D^+ \to K_S^0\pi^+$ in bins of ($p_\pi^{\rm lab}$, $\cos\theta_\pi^{\rm lab}$, $\cos\theta_{D^+}^{\rm CMS}$). Empty bins where no entries are plotted have no statistics.

The statistical precision of the $D_s^+ \to K_S^0\pi^+$ sample is too low to allow for a 3D correction to $A_{\rm rec}^{D_s^+\to K_S^0\pi^+}$. For this mode we correct for asymmetries other than A_{CP} with an inclusive correction obtained by subtracting $A_{\rm rec}^{D^+\to K_S^0\pi^+}$ from $A_{CP}^{D^+\to K_S^0\pi^+}$ after integrating over the entire ($p_\pi^{\rm lab}$, $\cos\theta_\pi^{\rm lab}$, $\cos\theta_{D^+}^{\rm CMS}$) space. The inclusive correction is $(-0.34 \pm 0.18)\%$ where the uncertainty is entirely due to the statistical uncertainty of the $D_s^+ \to \phi\pi^+$ sample. The value of $A_{CP}^{D_s^+\to K_S^0\pi^+}$ is measured to be $(+5.45 \pm 2.50)\%$, where the uncertainty is statistical only.

The dominant source of systematic uncertainty in the $A_{CP}^{D_{(s)}^+\to K_S^0\pi^+}$ measurement is the uncertainty in the $A_{\rm rec}^{D_s^+\to\phi\pi^+}$ determination, which originates from the following sources: the statistical uncertainty of the selected $D_s^+ \to \phi\pi^+$ sample (0.18%); the choice of the $M(K^+K^-)$ interval (0.03%); and the choice of binning for the 3D map of $A_{\rm rec}^{D_s^+\to\phi\pi^+}$ (0.03%). Another source is the choice of fitting parameters for the invariant mass distributions: binnings, mass windows, and background parametrizations together, contribute uncertainties of 0.04% to $A_{CP}^{D^+\to K_S^0\pi^+}$ and 0.27% to $A_{CP}^{D_s^+\to K_S^0\pi^+}$, where the larger uncertainty on $A_{CP}^{D_s^+\to K_S^0\pi^+}$ is inherited from the low statistics of $D_s^+ \to K_S^0\pi^+$. We also consider possible effects due to the differences in interactions of K^0 and $\bar{K}^0$ mesons with the material of the detector. K^0 and $\bar{K}^0$ mesons considered in this Letter are produced through the weak interaction and interact with

TABLE I. Summary of systematic uncertainties. σA_{CP} is the systematic uncertainty in A_{CP}.

Source		$\sigma A_{CP}^{D^+\to K_S^0\pi^+}$ (%)	$\sigma A_{CP}^{D_s^+\to K_S^0\pi^+}$ (%)	$\sigma A_{CP}^{D^+\to K_S^0K^+}$ (%)	$\sigma A_{CP}^{D_s^+\to K_S^0K^+}$ (%)
$A_{\rm rec}^{D_s^+\to\phi\pi^+}$	$D_s^+\to\phi\pi^+$ statistics	0.18	0.18	...	...
	$A_{\rm rec}^{D_s^+\to\phi\pi^+}$ binning	0.03	0.03	...	...
	$M(K^+K^-)$ window	0.03	0.03	...	...
$A_\epsilon^{K^-}$	$D_s^+\to\phi\pi^+$ statistics	...	...	0.18	0.18
	$A_{\rm rec}^{D_s^+\to\phi\pi^+}$ binning	...	...	0.03	0.03
	$M(K^+K^-)$ window	...	...	0.03	0.03
	$D^0\to K^-\pi^+$ statistics	...	...	0.06	0.06
	$A_\epsilon^{K^-}$ binning	...	...	0.04	0.04
	Possible $A_{CP}^{D^0\to K^-\pi^+}$	...	...	0.01	0.01
$\cos\theta_{D_{(s)}^+}^{\rm CMS}$ binning		...	...	0.06	0.06
Fitting		0.04	0.27	0.12	0.05
$K^0/\bar{K}^0$-material effects		0.06	0.06	0.06	0.06
Total		0.20	0.33	0.25	0.22

the material near the interaction point until they decay into $\pi^+\pi^-$ pairs. This produces a nonvanishing asymmetry originating from the different strong interactions of K^0 and $\bar{K}^0$ mesons with nucleons. Assuming that the differences between K^0 and $\bar{K}^0$ interactions with nucleons are the same as those for K^+ and K^- interactions, we calculate the probability of K^0 and $\bar{K}^0$-nucleons interactions using the known K^+ and K^- cross sections [3] and take into account the time evolution of neutral kaons. We consider the beam pipe [6] and the silicon vertex detector [9] in our estimates of the $K^0/\bar{K}^0$-material effects. The uncertainty in the CP asymmetry due to $K^0/\bar{K}^0$-material effects is found to be 0.06%. A summary of systematic uncertainties in $A_{CP}^{D_{(s)}^+\to K_S^0\pi^+}$ is given in Table I. By combining all systematic uncertainties in quadrature, we obtain $A_{CP}^{D^+\to K_S^0\pi^+} = (-0.71\pm 0.19\pm 0.20)\%$ and $A_{CP}^{D_s^+\to K_S^0\pi^+} = (+5.45\pm 2.50\pm 0.33)\%$, where the first uncertainties are statistical and the second are systematic.

The method for the measurement of A_{CP} in the $K_S^0K^+$ final states is different from that for the $K_S^0\pi^+$ final states. The $A_{\rm FB}^{D_{(s)}^+}$ and $A_\epsilon^{\pi^+}$ components in $A_{\rm rec}^{D_{(s)}^+\to K_S^0\pi^+}$ are directly obtained from the $D_s^+\to\phi\pi^+$ sample, but there is no corresponding large statistics decay mode that can be used to directly measure the $A_{\rm FB}^{D_{(s)}^+}$ and $A_\epsilon^{K^+}$ components in $A_{\rm rec}^{D_{(s)}^+\to K_S^0K^+}$. Thus, to correct the reconstructed asymmetry in the $K_S^0K^+$ final states, we use samples of $D^0\to K^-\pi^+$ as well as $D_s^+\to\phi\pi^+$ decays.

The measured asymmetry for $D^0\to K^-\pi^+$ is a sum of $A_{\rm FB}^{D^0}$, $A_\epsilon^{K^-}$, and $A_\epsilon^{\pi^+}$. Thus, we can extract $A_\epsilon^{K^-}$ by subtracting the measured asymmetry for $D_s^+\to\phi\pi^+$ from that for $D^0\to K^-\pi^+$. An $A_\epsilon^{K^-}$ correction map is obtained as follows: $N_{\rm rec}^{D^0\to K^-\pi^+}$ and $N_{\rm rec}^{\bar{D}^0\to K^+\pi^-}$ are corrected according to the reconstructed asymmetry for $D_s^+\to\phi\pi^+$ in bins of ($p_\pi^{\rm lab}$, $\cos\theta_\pi^{\rm lab}$, $\cos\theta_D^{\rm CMS}$). Subsequently, corrected $N_{\rm rec}^{D^0\to K^-\pi^+}$ and $N_{\rm rec}^{\bar{D}^0\to K^+\pi^-}$ values are determined in bins of $K^\mp$ momentum and polar angle in the laboratory frame ($p_{K^\mp}^{\rm lab}$, $\cos\theta_{K^\mp}^{\rm lab}$). From the corrected values of $N_{\rm rec}^{D^0\to K^-\pi^+}$ and $N_{\rm rec}^{\bar{D}^0\to K^+\pi^-}$ in bins of ($p_{K^\mp}^{\rm lab}$, $\cos\theta_{K^\mp}^{\rm lab}$), we obtain an $A_\epsilon^{K^-}$ map that is used to correct $A_\epsilon^{K^+}$ [10] for the $K_S^0K^+$ final states. By subtracting $A_\epsilon^{K^+}$ from the reconstructed asymmetry of $D_{(s)}^+\to K_S^0K^+$, we obtain the corrected reconstruction asymmetry $A_\epsilon^{K^+}$ for $D_{(s)}^+\to K_S^0K^+$:

$$A_{\rm rec}^{D_{(s)}^+\to K_S^0K_{\rm corr}^+} = A_{\rm rec}^{D_{(s)}^+\to K_S^0K^+} - A_\epsilon^{K^+} = A_{\rm FB}^{D_{(s)}^+} + A_{CP}^{D_{(s)}^+\to K_S^0K^+}. \tag{4}$$

As shown in Eq. (4), $A_{\rm rec}^{D_{(s)}^+\to K_S^0K_{\rm corr}^+}$ includes not only an A_{CP} component but also an $A_{\rm FB}$ component. Since A_{CP} is independent of all kinematic variables, while $A_{\rm FB}$ is an odd function of $\cos\theta_{D_{(s)}^+}^{\rm CMS}$, and thus vanishes when integrated over it, we measure $A_{\rm rec}^{D_{(s)}^+\to K_S^0K_{\rm corr}^+}$ as a function of $\cos\theta_{D_{(s)}^+}^{\rm CMS}$. The A_{CP} component in Eq. (4) is then extracted according to Eq. (5a), using the above symmetry properties. We also extract the $A_{\rm FB}$ component in Eq. (4) using Eq. (5b).

$$A_{CP}^{D_{(s)}^+\to K_S^0K^+} = [A_{\rm rec}^{D_{(s)}^+\to K_S^0K_{\rm corr}^+}(\cos\theta_{D_{(s)}^+}^{\rm CMS}) + A_{\rm rec}^{D_{(s)}^+\to K_S^0K_{\rm corr}^+}(-\cos\theta_{D_{(s)}^+}^{\rm CMS})]/2, \tag{5a}$$

$$A_{\rm FB}^{D_{(s)}^+\to K_S^0K^+} = [A_{\rm rec}^{D_{(s)}^+\to K_S^0K_{\rm corr}^+}(\cos\theta_{D_{(s)}^+}^{\rm CMS}) - A_{\rm rec}^{D_{(s)}^+\to K_S^0K_{\rm corr}^+}(-\cos\theta_{D_{(s)}^+}^{\rm CMS})]/2. \tag{5b}$$

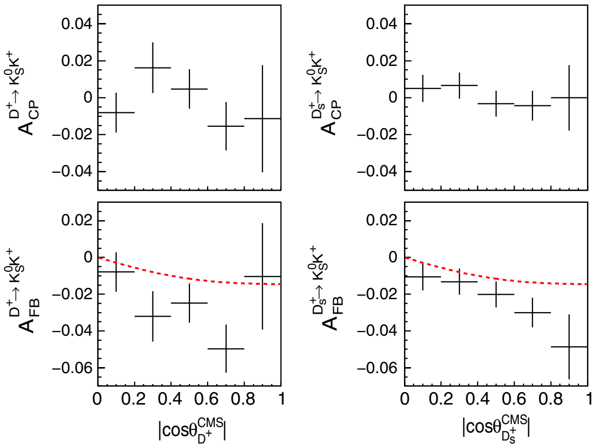

FIG. 3 (color online). Measured A_{CP} and A_{FB} values for $D^+_{(s)} \to K^0_S K^+$ as a function of $|\cos\theta^{CMS}_{D^+_{(s)}}|$. The dashed curves show the leading-order prediction for $A^{c\bar{c}}_{FB}$.

Figure 3 shows $A_{CP}^{D^+_{(s)} \to K^0_S K^+}$ and $A_{FB}^{D^+_{(s)} \to K^0_S K^+}$ as a function of $|\cos\theta^{CMS}_{D^+_{(s)}}|$. Calculating a weighted average over the $|\cos\theta^{CMS}_{D^+_{(s)}}|$ bins, we obtain $A_{CP}^{D^+ \to K^0_S K^+} = (-0.16 \pm 0.58)\%$ and $A_{CP}^{D^+_s \to K^0_S K^+} = (+0.12 \pm 0.36)\%$ where the uncertainties are statistical only. The observed A_{FB} values decrease with $\cos\theta^{CMS}_{D^+_{(s)}}$ as expected from the leading-order prediction [11]. The observed deviations from the prediction are expected due to higher order corrections, and are in agreement with the measured asymmetries in the K^+K^- and $\pi^+\pi^-$ final states [12].

The dominant source of systematic uncertainty in the $A_{CP}^{D^+_{(s)} \to K^0_S K^+}$ measurement is the uncertainty in $A_\epsilon^{K^-}$, which has several sources: the systematic uncertainty in the $A_{rec}^{D^+_s \to \phi\pi^+}$ measurement (0.18%); statistics of the $D^0 \to K^-\pi^+$ sample (0.06%); the systematic uncertainty due to the choice of binning for the two-dimensional map of $A_\epsilon^{K^-}$ (0.04%); and a possible A_{CP} in the $D^0 \to K^-\pi^+$ final state from the interference between decays with and without $D^0 - \bar{D}^0$ mixing. The latter uncertainty is estimated from the 95% confidence level upper limit on the CP violating asymmetry, $A_{CP} = -y \sin\delta \sin\phi \sqrt{R}$ [13], using the world average of $D^0 - \bar{D}^0$ mixing and CP violation parameters [14] and is found to be 0.01%. We also consider different $\cos\theta^{CMS}_{D^+_{(s)}}$ binnings to estimate the systematic uncertainty due to the choice of $\cos\theta^{CMS}_{D^+_{(s)}}$ binning (0.06%). Systematic uncertainties due to the fitting procedure and $K^0/\bar{K}^0$-material effects are described above and included in Table I, where the total systematic uncertainties of the A_{CP} measurements are summarized. Combining all systematic uncertainties in quadrature, we obtain $A_{CP}^{D^+ \to K^0_S K^+} = (-0.16 \pm 0.58 \pm 0.25)\%$ and $A_{CP}^{D^+_s \to K^0_S K^+} = (+0.12 \pm 0.36 \pm 0.22)\%$ where the first uncertainties are statistical and the second are systematic. Table II summarizes our results, present best measurements [15], and expected A_{CP} from $K^0 - \bar{K}^0$ mixing [3].

In summary, with a 673 fb^{-1} data sample collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider, we have searched for CP violation in the charged charmed meson decays $D^+_{(s)} \to K^0_S \pi^+$ and $D^+_{(s)} \to K^0_S K^+$. No evidence for CP violation is observed. Our results are consistent with the SM (see Table II) and provide the most stringent constraints to date on models for beyond the SM CP violation in these decays [5].

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TABLE II. Summary of the A_{CP} measurements. The first uncertainties in the second and third columns are statistical and the second are systematic. DCS decay contributions are ignored for the decays denoted by †'s in the fourth column.

	Belle (%)	Ref. [15] (%)	Ref. [3] (%)
$A_{CP}^{D^+ \to K^0_S \pi^+}$	$-0.71 \pm 0.19 \pm 0.20$	$-1.3 \pm 0.7 \pm 0.3$	$-0.332^\dagger$
$A_{CP}^{D^+_s \to K^0_S \pi^+}$	$+5.45 \pm 2.50 \pm 0.33$	$+16.3 \pm 7.3 \pm 0.3$	$+0.332$
$A_{CP}^{D^+ \to K^0_S K^+}$	$-0.16 \pm 0.58 \pm 0.25$	$-0.2 \pm 1.5 \pm 0.9$	-0.332
$A_{CP}^{D^+_s \to K^0_S K^+}$	$+0.12 \pm 0.36 \pm 0.22$	$+4.7 \pm 1.8 \pm 0.9$	$-0.332^\dagger$

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[10] We define $A^{x^+} \equiv [N^{x^+} - N^{x^-}]/[N^{x^+} + N^{x^-}]$. Hence $A^{x^-} = -A^{x^+}$.
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