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

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Violation of the combined Charge-conjugation and Parity symmetries (CP) in the standard model (SM) is produced by a non-vanishing phase in the Cabibbo-Kobayashi-Maskawa flavor-mixing matrix \[^{35}\text{Riken BNL Research Center, Upton, New York 11973}^\text{36}\text{University of Science and Technology of China, Hefei}^\text{37}\text{Seoul National University, Seoul}^\text{38}\text{Sungkyunkwan University, Suwon}^\text{39}\text{School of Physics, University of Sydney, NSW 2006}^\text{40}\text{Tata Institute of Fundamental Research, Mumbai}^\text{41}\text{Excellence Cluster Universe, Technische Universität München, Garching}^\text{42}\text{Toho University, Funabashi}^\text{43}\text{Tohoku Gakuen University, Tagajo}^\text{44}\text{Tohoku University, Sendai}^\text{45}\text{Department of Physics, University of Tokyo, Tokyo}^\text{46}\text{Tokyo Metropolitan University, Tokyo}^\text{47}\text{Tokyo University of Agriculture and Technology, Tokyo}^\text{48}\text{IPNAS, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061}^\text{49}\text{Yonsei University, Seoul}\]

The SM also predicts a semileptonic decay \(^{38}\text{K}^0\to\pi^+\ell^+\bar{\nu}_\ell\), which is produced by a non-vanishing phase in the Cabibbo-Kobayashi-Maskawa flavor-mixing matrix \[^{35}\text{Riken BNL Research Center, Upton, New York 11973}^\text{36}\text{University of Science and Technology of China, Hefei}^\text{37}\text{Seoul National University, Seoul}^\text{38}\text{Sungkyunkwan University, Suwon}^\text{39}\text{School of Physics, University of Sydney, NSW 2006}^\text{40}\text{Tata Institute of Fundamental Research, Mumbai}^\text{41}\text{Excellence Cluster Universe, Technische Universität München, Garching}^\text{42}\text{Toho University, Funabashi}^\text{43}\text{Tohoku Gakuen University, Tagajo}^\text{44}\text{Tohoku University, Sendai}^\text{45}\text{Department of Physics, University of Tokyo, Tokyo}^\text{46}\text{Tokyo Metropolitan University, Tokyo}^\text{47}\text{Tokyo University of Agriculture and Technology, Tokyo}^\text{48}\text{IPNAS, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061}^\text{49}\text{Yonsei University, Seoul}\]

In this Letter we report results from searches for CP violation in the charmed meson decays \(^{46}\text{D}^+_s\to\text{K}^{0}\text{s}\pi^+\) and \(^{46}\text{D}^+_s\to\text{K}^{0}\text{s}K^+\) 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: \(^{46}\text{A}_{CP}^{D^+_s\to\text{K}^{0}\text{s}\pi} = (-0.71 \pm 0.19 \pm 0.20)\%\), \(^{46}\text{A}_{CP}^{D^+_s\to\text{K}^{0}\text{s}K} = (5.45 \pm 2.50 \pm 0.33)\%\), \(^{46}\text{A}_{CP}^{D^+_s\to\text{K}^{0}\text{h}^+} = (-0.16 \pm 0.58 \pm 0.25)\%\), and \(^{46}\text{A}_{CP}^{D^+_s\to\text{K}^{0}\text{s}h} = (0.12 \pm 0.36 \pm 0.22)\%\), where the first uncertainties are statistical and the second are systematic.

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symmetry other than $A^{h+}_\epsilon$. Eq. (2) can therefore be expressed as

$$A_{rec}^{X^+\to K^0_S h^+} = A_{CP}^{X^+\to K^0_S h^+} + A_{FB}^{h+} + A^{h+}_{\epsilon}.$$ (3)

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

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

The statistical precision of the $D_s^+ \rightarrow K^0_S \pi^+$ sample is too low to allow for a 3-D correction to $A_{rec}^{D_s^+\to K^0_S \pi^+}$. For this mode we correct for asymmetries other than $A_{CP}$ with an inclusive correction obtained by subtracting $A_{rec}^{D^+\to K^0_S \pi^+}$ from $A_{CP}^{D^+\to K^0_S \pi^+}$ after integrating over the entire $(p_{\pi}^{lab}, \cos \theta_{\pi}^{lab}, \cos \theta_{CMS}^{D^+})$ space. The inclusive correction is $(-0.34 \pm 0.18\%)$ where the uncertainty is entirely due to the statistical uncertainty of the $D_s^+ \rightarrow \phi \pi^+$ sample. The value of $A_{CP}^{D^+\to K^0_S \pi^+}$ is measured to be $(+5.45 \pm 2.50\%)$, where the uncertainty is statistical only.
tributions: binnings, mass windows, and background parameterizations together, contribute uncertainties of 0.04% to $A_{CP}^{D^+ \rightarrow K^0 \pi^+}$ and 0.27% to $A_{CP}^{D^+ \rightarrow K^0 \pi^+}$, where the larger uncertainty on $A_{CP}^{D^+ \rightarrow K^0 \pi^+}$ is inherited from the low statistics of $D^+_s \rightarrow K^0 \pi^+$. We also consider possible effects due to the differences in interactions of $K^0$ and $K^0$ mesons with the material of the detector. $K^0$ and $K^0$ mesons considered in this Letter are produced through the weak interaction and interact with the material near the interaction point until they decay into $\pi^+ \pi^-$ pairs. This produces a non-vanishing asymmetry originating from the different strong interactions of $K^0$ and $K^0$ mesons with nucleons. Assuming that the differences between $K^0$ and $K^0$ interactions with nucleons are the same as those for $K^+$ and $K^-$ interactions, we calculate the probability of $K^0$ and $K^0$-nucleon interactions using the known $K^+$ and $K^-$ cross sections [9] and take into account the time evolution of neutral kaons. We consider the beam pipe [6] and the silicon vertex detector [3] in our estimates of the $K^0$/$K^0$-material effects. The uncertainty in the CP asymmetry due to $K^0$/$K^0$-material effects is found to be 0.06%. A summary of systematic uncertainties in $A_{CP}^{D^+_s \rightarrow K^0 \pi^+}$ is given in Table I.

By combining all systematic uncertainties in quadrature, we obtain $A_{CP}^{D^+ \rightarrow K^0 \pi^+} = (-0.71 \pm 0.19 \pm 0.20)\%$ and $A_{CP}^{D^+ \rightarrow K^0 \pi^+} = (+5.45 \pm 2.50 \pm 0.33)\%$, where the first uncertainties are statistical and the second are systematic.

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

The measured asymmetry for $D^0 \rightarrow K^- \pi^+$ is a sum of $A_{FB}^{p}$, $A_{FB}^{K^-}$, and $A_{FB}^{K^+}$. Thus, we can extract $A_{FB}^{K^-}$ from $D^0 \rightarrow K^- \pi^+$, which has several sources: the systematic uncertainty in the $A_{FB}^{D^+ \rightarrow \phi \pi^+}$ measurement (0.18%); statistics of the $D^0 \rightarrow K^- \pi^+$ sample (0.06%); the systematic uncertainty due to the choice of binning for the 2-D map of $A_{FB}^{K^-}$ (0.04%); and a possible $A_{CP}$ in the $D^0 \rightarrow K^- \pi^+$ final state from the interference between decays with and without $D^0 \rightarrow D^0$ mixing. The latter uncertainty is estimated from the 95% confidence level upper limit on the $CP$ violating asymmetry, $A_{CP} = -y \sin \delta \sin \phi \sqrt{2}$ [13], using the world average of $D^0 \rightarrow D^0$ mixing and $CP$ violating parameters [14] and is found to be 0.01%. We also consider different cos$\theta$ CMS binnings to estimate the systematic uncertainty due to the choice of cos$\theta$ CMS binning.

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

$$A_{CP}^{D^+_s \rightarrow K^0_S K^+} = |A_{rec}^{D^+_s \rightarrow K^0_S K^+}(\cos \theta_{CMS}^{D^+_s})|,$$

$$A_{FB}^{D^+_s \rightarrow K^0_S K^+} = |A_{rec}^{D^+_s \rightarrow K^0_S K^+}(\cos \theta_{CMS}^{D^+_s})|/2,$$

Figure 3 shows $A_{CP}^{D^+_s \rightarrow K^0_S K^+}$ and $A_{FB}^{D^+_s \rightarrow K^0_S K^+}$ as a function of cos$\theta$ CMS $D^+_s$. Calculating a weighted average over the $|\cos \theta_{CMS}^{D^+_s}|$ bins, we obtain $A_{CP}^{D^+_s \rightarrow K^0_S K^+} = (-0.16 \pm 0.58)\%$ and $A_{FB}^{D^+_s \rightarrow K^0_S K^+} = (0.12 \pm 0.36)\%$ where the uncertainties are statistical only. The observed $A_{FB}$ values decrease with cos$\theta$ CMS 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 $A_{CP}^{D^+_s \rightarrow K^0_S K^+}$ measurement is the uncertainty in $A_{CP}^{K^-}$, which has several sources: the systematic uncertainty in the $A_{CP}^{D^+_s \rightarrow \phi \pi^+}$ measurement (0.18%); statistics of the $D^0 \rightarrow K^- \pi^+$ sample (0.06%); the systematic uncertainty due to the choice of binning for the 2-D map of $A_{CP}^{K^-}$ (0.04%); and a possible $A_{CP}$ in the $D^0 \rightarrow K^- \pi^+$ final state from the interference between decays with and without $D^0 \rightarrow D^0$ mixing. The latter uncertainty is estimated from the 95% confidence level upper limit on the $CP$ violating asymmetry, $A_{CP} = -y \sin \delta \sin \phi \sqrt{2}$ [13], using the world average of $D^0 \rightarrow D^0$ mixing and $CP$ violating parameters [14] and is found to be 0.01%. We also consider different cos$\theta$ CMS binnings to estimate the systematic uncertainty due to the choice of cos$\theta$ CMS 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 \(A^{D^+\rightarrow K_S^0 K^+}_{CP} = (-0.16 \pm 0.58 \pm 0.25)\%\) and \(A^{D_s^+\rightarrow K_S^0 K^+}_{CP} = (+0.12 \pm 0.36 \pm 0.22)\%\) where the first uncertainties are statistical and the second are systematic. Table II summarizes our results, present best measurements \cite{13}, and expected \(A_{CP}\) from \(K^0 - \bar{K}^0\) mixing \cite{3}.

![FIG. 3: Measured \(A_{CP}\) and \(A_{FB}\) values for \(D^{+}_{(s)} \rightarrow K_S^0 K^+\) as a function of |\(cos\theta^{CMS}_{D^+}\)|. The dashed curves show the leading-order prediction for \(A_{FB}\).](image)

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 \(D^+_{(s)} \rightarrow K_S^0 \pi^+\) and \(D^+_{(s)} \rightarrow K_S^0 K^+\). 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 \cite{3}.

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\[\text{Table I: Summary of systematic uncertainties.} \sigma A_{CP}\text{ is the systematic uncertainty in }A_{CP}.\]

| Source                             | \(\sigma A^{D^+\rightarrow K_S^0 \pi^+}_{CP}\) (%) | \(\sigma A^{D^+\rightarrow K_S^0 K^+}_{CP}\) (%) | \(\sigma A^{D_s^+\rightarrow K_S^0 K^+}_{CP}\) (%) |
|------------------------------------|-------------------------------------------------|------------------------------------------------|------------------------------------------------|
| \(A^{D^+\rightarrow \phi \pi^+}_{rec}\) statistics | 0.18                                            | 0.18                                            | -                                              |
| \(A^{D^+\rightarrow \phi \pi^+}_{binning}\) | 0.03                                            | 0.03                                            | -                                              |
| \(M(K^+ K^-)\) window               | -                                               | -                                               | 0.03                                           |
| \(A^{K^-}_{binning}\)               | -                                               | -                                               | 0.04                                           |
| Possible \(A^{D_s^+\rightarrow K^- \pi^+}_{binning}\) | -                                               | -                                               | 0.01                                           |
| \(\cos \theta^{CMS}_{D^+}\)        | -                                               | -                                               | 0.06                                           |
| Fitting                            | 0.04                                            | 0.27                                            | 0.12                                           |
| \(K^0/\bar{K}^0\)-material effects | 0.06                                            | 0.06                                            | 0.06                                           |
| Total                              | 0.20                                            | 0.33                                            | 0.25                                           |

\[\text{Table II: Summary of the }A_{CP}\text{ measurements. The first uncertainties in the second and third columns are statistical and the second are systematic. DCS decay contributions are ignored for the decays denoted by }\dagger\text{.}\]

| \(Belle\) (%) | Ref. \cite{15} (%) | Ref. \cite{3} (%) |
|----------------|-------------------|-------------------|
| \(A^{D^+\rightarrow K_S^0 \pi^+}_{CP}\) | -0.71\(\pm\)0.19\(\pm\)0.20 | -1.3\(\pm\)0.7\(\pm\)0.3 | -0.332\(\dagger\) |
| \(A^{D^+\rightarrow K_S^0 K^+}_{CP}\) | +5.45\(\pm\)2.50\(\pm\)0.33 | +16.3\(\pm\)7.3\(\pm\)0.3 | +0.332 |
| \(A^{D_s^+\rightarrow K_S^0 K^+}_{CP}\) | -0.16\(\pm\)0.58\(\pm\)0.25 | -0.2\(\pm\)1.5\(\pm\)0.9 | -0.332 |
| \(A^{D_s^+\rightarrow K_S^0 K^+}_{CP}\) | +0.12\(\pm\)0.36\(\pm\)0.22 | +4.7\(\pm\)1.8\(\pm\)0.9 | -0.332\(\dagger\) |
Throughout this Letter the charge conjugate decay mode is also implied unless stated otherwise.

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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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