Search for CP Violation in the Decays $D^0 \to K_S^0 P^0$

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We have searched for CP violation in the decays \(D^0 \to K_S^0 P^0\) where \(P^0\) denotes a neutral pseudo-scalar meson that is either a \(\pi^0\), \(\eta\), or \(\eta'\) using KEKB asymmetric-energy \(e^+e^-\) collision data corresponding to an integrated luminosity of 791 fb\(^{-1}\) collected with the Belle detector. No evidence of significant CP violation is observed. We report the most precise CP asymmetry measurement in the decay \(D^0 \to K_S^0 \pi^0\) to date: \(A_{CP}^{D^0 \to K_S^0 \pi^0} = \langle -0.28 \pm 0.19 \pm 0.10 \rangle\%\). We also report the first measurements of CP asymmetries in the decays \(D^0 \to K_S^0 \eta\) and \(D^0 \to K_S^0 \eta'\): \(A_{CP}^{D^0 \to K_S^0 \eta} = \langle +0.54 \pm 0.51 \pm 0.16 \rangle\%\) and \(A_{CP}^{D^0 \to K_S^0 \eta'} = \langle +0.98 \pm 0.67 \pm 0.14 \rangle\%\), respectively.

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The recent evidence for \(D^0 - \bar{D}^0\) mixing \cite{1, 3} and the corresponding mixing parameters \cite{4} are at the upper edge of standard model (SM) predictions \cite{5}. However, large theoretical uncertainties in these predictions limit the sensitivity to effects of physics beyond the SM. An alternative, potentially more promising approach to search for new physics (NP) is the study of violation of the combined Charge-conjugation and Parity symmetries (CP) in the decays of charmed mesons \cite{6}. In contrast to mixing, the expected SM CP violation in the charm sector is small \cite{2}.

In this Letter we report time-integrated CP asymmetry measurements in the decays \(D^0 \to K_S^0 P^0\) \cite{6} where \(P^0\) denotes a neutral pseudo-scalar meson: \(\pi^0\), \(\eta\), or \(\eta'\). The time-integrated asymmetry, \(A_{CP}\), is defined as

\[
A_{CP}^{D^0 \to K_S^0 P^0} = \frac{\Gamma(D^0 \to K_S^0 P^0) - \Gamma(D^0 \to \bar{K}_S^0 P^0)}{\Gamma(D^0 \to K_S^0 P^0) + \Gamma(D^0 \to \bar{K}_S^0 P^0)},
\]

where \(\Gamma\) is the partial decay width.

The observed \(K_S^0 P^0\) final states are mixtures of \(D^0 \to \bar{K}_0^0 P^0\) and \(D^0 \to K_0^0 P^0\) decays where the former are Cabibbo-favored (CF) and the latter are doubly Cabibbo-suppressed (DCS). In the absence of direct CP violation in CF and DCS decays, as expected in the SM, the CP violation in these processes within the SM is generated from mixing and interference of decays with and without mixing, which is parameterized by \(a_{ind}\) (where we adopt the symbols used in Ref. \cite{6}). SM \(K^0 - \bar{K}^0\) mixing leads to a small CP asymmetry in final states containing a neutral kaon, even if no CP violating phase exists in the charm decay. The asymmetry that is expected from the SM is measured to be \((-0.332 \pm 0.006)\%\) \cite{9} from \(K_0^0\) semileptonic decays and referred to as \(A_{CP}^{K_0^0 \pi^0}\) \cite{10}, which is reflected in the value of \(A_{CP}^{D^0 \to K_S^0 P^0}\) if DCS decay contributions are ignored. Since the \(a_{ind}\) value expected from the SM is at most \(O(10^{-4})\) \cite{6, 7}, the value of CP asymmetry in the decays \(D^0 \to K_S^0 P^0\) within the SM is approximately \(A_{CP}^{K_0^0 \pi}\). On the other hand, if NP processes contain additional weak phases other than the one in the Kobayashi-Maskawa ansatz \cite{11}, interferences between CF and DCS decays could generate \(O(1\%)\) direct CP asymmetry in the decays \(D^0 \to K_0^0 P^0\) \cite{12}. Physics beyond the SM could also induce \(O(1\%)\) indirect CP asymmetry \cite{6}. Thus, observing \(A_{CP}\) inconsistent with \(A_{CP}^{K_0^0 \pi}\) in \(D^0 \to K_0^0 P^0\) decays would be strong evidence for processes involving physics beyond the SM \cite{6, 12}.

In addition to \(A_{CP}\) measurements, we examine the universality of \(a_{ind}\) in \(D^0\) decays \cite{6} by comparing our previous result \cite{2} with the \(A_{CP}^{D^0 \to K_S^0 \pi^0}\) value reported in this Letter. Our previously measured values of direct CP violation asymmetries (denoted \(a_{D^0 \to K^+ K^-}\) \cite{6}, \(a_{D^0 \to \pi^+ \pi^-}\) \cite{13}) are also updated.

The decay \(D^{*+} \to D^0 \pi^+\) is used to identify the flavor of the \(D^0\) meson from the charge of the low momentum pion (referred to as “the soft pion”), \(\pi^+\). Thus, we determine \(A_{CP}^{D^*+ \to K_S^0 P^0}\) by measuring the asymmetry in the signal yield

\[
A_{rec}^{D^{*+} \to D^0 \pi^+} = \frac{N_{rec}^{D^{*+} \to D^0 \pi^+} - N_{rec}^{D^{*+} \to D^0 \pi^-}}{N_{rec}^{D^{*+} \to D^0 \pi^+} + N_{rec}^{D^{*+} \to D^0 \pi^-}},
\]
where \( N_{\text{rec}} \) is the number of reconstructed decays. The measured asymmetry in Eq. 2 includes two contributions other than \( A_{CP} \). One is the forward-backward asymmetry \( (A_{FB}) \) due to \( \gamma^+ - Z^0 \) interference in \( e^+e^- \rightarrow c\bar{c} \) and the other is a detection efficiency asymmetry between positively and negatively charged soft pions \( (A_{\pi}^{\pm}) \).

Since we reconstruct the \( K_S^0 \) with \( \pi^+\pi^- \) combinations and \( p^0 \) with the \( \gamma \gamma \) or \( \gamma \gamma\pi^+\pi^- \) final states, asymmetries in \( K_S^0 \) and \( p^0 \) detection cancel out. Equation 2 can be simplified to give

\[
A_{\text{rec}}^{D^+ \rightarrow D^0\pi^+} = A_{\text{CP}}^{D^0 \rightarrow K_S^0 p^0} + A_{FB}^{D^+} (\cos \theta_{D^+}^{\text{CMS}}) + A_{\text{tag}}^{D^+} (p_{T\pi^+}^{\text{lab}}, \cos \theta_{\pi^+}^{\text{lab}})
\]

(3)

by neglecting the terms involving the product of asymmetries, where \( A_{CP} \) is independent of all kinematic variables, \( A_{FB}^{D^+} \) is an odd function of the cosine of the polar angle of \( D^+ \) in the center-of-mass system (CMS), and \( A_{\text{tag}}^{D^+} \) depends on transverse momentum and polar angle of \( \pi^+ \) in the laboratory frame, while it is uniform in azimuthal angle. To correct for \( A_{\text{tag}}^{D^+} \), we use the decays \( D^0 \rightarrow K^\pm \pi^\mp \) (referred to as untagged) and \( D^+ \rightarrow D^0\pi^+ \rightarrow K^\pm \pi^\mp \pi^\pm \) (referred to as tagged), and assumes the same \( A_{FB} \) for \( D^+ \) and \( D^0 \) mesons. By subtracting the measured asymmetries in these two decay modes, \( A_{\text{rec}}^{D^+} \) and \( A_{\text{rec}}^{D^0} \), we directly measure the \( A_{\text{Tag}}^{D^+} \) correction factor \( 13, 14 \). With \( A_{\text{Tag}}^{D^+ \rightarrow D^0\pi^+} \) corrected for \( A_{\text{Tag}}^{D^+} \) (denoted \( A_{\text{rec,corr}}^{D^+ \rightarrow D^0\pi^+} \) below),

\[
A_{\text{rec,corr}}^{D^+ \rightarrow D^0\pi^+} = A_{\text{CP}}^{D^0 \rightarrow K_S^0 p^0} + A_{FB}^{D^+} (\cos \theta_{D^+}^{\text{CMS}})
\]

(4)

we extract \( A_{CP} \) and \( A_{FB} \) using

\[
A_{\text{CP}}^{D^0 \rightarrow K_S^0 p^0} = [A_{\text{Tag}}^{D^+ \rightarrow D^0\pi^+} (\cos \theta_{D^+}^{\text{CMS}})]/2,
\]

\[
A_{FB}^{D^+} = [A_{\text{Tag}}^{D^+ \rightarrow D^0\pi^+} (\cos \theta_{D^+}^{\text{CMS}})] - A_{\text{Tag}}^{D^+ \rightarrow D^0\pi^+} (\cos \theta_{D^+}^{\text{CMS}})]/2.
\]

(5a)

(5b)

The data used in this analysis were recorded at or near the \( \Upsilon(4S) \) resonance with the Belle detector \( 15 \) at the \( e^+e^- \) asymmetric-energy collider KEKB \( 16 \). The sample corresponds to an integrated luminosity of 791 fb\(^{-1}\).

We apply the same charged track selection criteria that were used in Ref. 17. For soft pions we do not require associated hits in the silicon vertex detector, either in the \( z \) or radial directions \( 18 \). Charged kaons and pions are identified by requiring the ratio of particle identification likelihoods \( 17 \) to be greater or less than 0.6, respectively. \( K_S^0 \) candidates are reconstructed from pairs of oppositely charged tracks that have an invariant mass within \( \pm 9 \text{ MeV}/c^2 \) of the nominal \( K_S^0 \) mass \( 9 \). Candidate \( \pi^0 \) and \( \eta \) mesons are reconstructed from \( \gamma \gamma \) pairs where the minimum energy of each \( \gamma \) is required to be 60 MeV for the barrel and 100 MeV for the forward region of the calorimeter \( 19 \). We require the \( \gamma \gamma \) invariant mass to be between 0.11 and 0.16 GeV/c\(^2\) for \( \pi^0 \) candidates and between 0.50 and 0.58 GeV/c\(^2\) for \( \eta \) candidates. The momentum of \( \gamma \gamma \) pairs is required to be greater than 0.5 GeV/c for both \( \pi^0 \) and \( \eta \) selections. In order to remove a significant \( \pi^0 \) photon background contribution under the \( \eta \) signal peak, we combine individual \( \gamma \) candidates from \( \eta \rightarrow \gamma \gamma \) with any other detected \( \gamma \) in the event. If the \( \gamma \gamma \) pair invariant mass is in the \( \pi^0 \) mass window, the \( \gamma \) is rejected. Further reduction of the \( \pi^0 \) contribution under the \( \eta \) signal is achieved by requiring the energy balance of the \( \gamma \gamma \) in the \( \eta \) decay to be less than 0.8, where the energy balance is the ratio of the difference and the sum of two \( \gamma \) energies. Candidate \( \eta \) mesons are reconstructed in the \( \eta \pi^+\pi^- \) decay channel. To improve the \( \eta' \) mass-resolution, the four-momentum of the \( \eta \) is recalculated with a nominal \( \eta \) mass \( 9 \) constraint. The same minimum \( \gamma \) energy requirement used for the \( D^0 \rightarrow K_S^0 \eta \) selection is imposed in the \( \eta' \) reconstruction. The \( \pi^0 \) veto, however, is not applied since it is found to be unnecessary once the invariant mass of the \( \eta \pi^+\pi^- \) candidates is required to be between 0.945 and 0.970 GeV/c\(^2\) and the \( D^0 \) mass selection requirement, which is described below, is applied.

The four-momentum of the \( p^0 \) is recalculated from a kinematic fit to its nominal mass \( 9 \) and combined with a \( K_S^0 \) to form a \( D^0 \) candidate. \( D^+ \) candidates are reconstructed using a soft pion and a \( D^0 \) candidate with mass in the \([1.75, 1.95]\) GeV/c\(^2\) \( (K_S^0\pi^0) \), \([1.82, 1.90]\) GeV/c\(^2\) \( (K_S^0\eta) \), or \([1.84, 1.89]\) GeV/c\(^2\) \( (K_S^0\eta') \) interval which depends on the mass resolution. To remove \( D^+ \) mesons produced in \( B \) decays, the \( D^+ \) momentum in the CMS is required to be greater than 2.5 GeV/c. All selections are chosen to maximize \( N_S/\sigma_N \) and to minimize the peaking backgrounds, where \( N_S \) is the signal yield from the fit and \( \sigma_N \) is the uncertainty in \( N_S \). After applying all of the selections described above, the \( D^0 \rightarrow \pi^+\pi^-\pi^0 \) contribution to \( D^0 \rightarrow K_S^0 \pi^0 \) and the \( D^0 \rightarrow K_S^0\pi^0 \) contribution to \( D^0 \rightarrow K_S^0 \eta \) are found to be negligible in simulation studies. Figure 4 shows data distributions of the mass difference \( M(D^+) - M(D) \) for all the decay modes.

All mass difference signals are parameterized as a sum of a Gaussian and a bifurcated Gaussian distributions with a common mean. The background is parameterized by the form \( (x - m_{\pi^+})^3 e^{-\beta(x-m_{\pi^+})} \), where \( \alpha \) and \( \beta \) are free parameters, \( m_{\pi^+} \) is the charged pion mass \( 9 \) and \( x \) is the mass difference. 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. The common parameters in the simultaneous fit are the mean of the Gaussian, the widths of the Gaussian and the bifurcated Gaussian, and the ratio of the Gaussian and the bifurcated Gaussian amplitudes, which are
the same for the $M(D^*) - M(D)$ distributions in different $K_S^0 p^0$ final states and in the slightly different phase spaces of the individual $K_S^0 p^0$ modes. Table I lists the results of the fits.

TABLE I: The sum (of the parameterizations of the data. Hatched areas are the error bars are the data and the histograms show the results of the fits.

| $N_S$ | $A_{	ext{rec}}$ (°) |
|-------|------------------|
| $D^{*-} \rightarrow D^0 \pi^+ \rightarrow K_S^0 \pi^+ \pi^+$ | 326303 $\pm$ 679 | $+0.19 \pm 0.19$ |
| $D^{*-} \rightarrow D^0 \pi^+ \rightarrow K_S^0 \pi^+ \pi^+$ | 45831 $\pm$ 283 | $+1.00 \pm 0.51$ |
| $D^{*-} \rightarrow D^0 \pi^+ \rightarrow K_S^0 \pi^+ \pi^+$ | 26899 $\pm$ 211 | $+1.47 \pm 0.67$ |

In order to obtain $A^{\pi^+}$, we first extract $A^{\text{untagged}}$ using simultaneous fits analogous to those used for the signal modes, but instead of the $M(D^*) - M(D)$ distribution we fit to the $M(D)$ distribution using a similar parameterization. The values of $A^{\text{untagged}}$ are evaluated in bins of transverse momentum ($p_{T\text{lab}}$) and polar angle ($\cos \theta_{\text{lab}}$) of untagged $D^0 \rightarrow K^- \pi^+$ candidates in the laboratory frame. The $p_T$ and polar angle variables are only weakly correlated. Each tagged $D^* \rightarrow D \pi_s \rightarrow K \pi_s \pi_s$ candidate is then weighted with $1 - A^{\text{untagged}}$ for $D^{*+}$ and $1 + A^{\text{untagged}}$ for $D^{*-}$. Details of the weighting procedure are described in Ref. [13]. After this the remaining asymmetry in the tagged decay sample is $A^{\pi^+}$, which is obtained from the simultaneous fits to the weighted $M(D^*) - M(D)$ distributions with the same parameterization used in the signal modes, now for bins of $p_{T\text{lab}} ^{A^{\pi^+}}$ and $\cos \theta_{\text{lab}} ^{A^{\pi^+}}$.

The dominant sources of uncertainty in the $A^{\pi^+}$ determination are the statistical uncertainties in the untagged and tagged samples. These are found to be 0.04% and 0.07%, respectively. Other sources of systematic uncertainties are found to be negligible. Thus, we assign a total systematic uncertainty of 0.08% to the $A^{\pi^+}$ determination, obtained by adding the two contributions in quadrature.

The data samples shown in Fig. 1 are divided into bins of $p_{T\text{lab}}$ and $\cos \theta_{\text{lab}}$ of the $\pi^+$. The $A^{\pi^+}$ correction is applied by weighting each $D^{*+}$ event with $1 - A^{\pi^+}$ and each $D^{-*}$ event with $1 + A^{\pi^+}$. The weighted mass difference distributions in bins of the $D^{*+}$ polar angle in the CMS are fitted simultaneously to obtain the corrected asymmetry. We fit for the linear component in $\cos \theta_{\text{CMS}}$ to determine $A_{FB}$ while the $A_{CP}$ component is uniform in $\cos \theta_{\text{CMS}}$.

![FIG. 1: Distributions of the mass difference $M(D^*) - M(D)$ for the studied decay modes. Left plots show the mass difference between $D^{*+}$ and $D^0$ and right plots show that between $D^{-*}$ and $D^0$. Top plots are for the $K_S^0 \pi^0$, middle plots for the $K_S^0 \eta$, and bottom plots for the $K_S^0 \eta'$ final states. Points with error bars are the data and the histograms show the results of the parameterizations of the data. Hatched areas are the background contributions.](image)

![FIG. 2: Measured $A_{CP}$ (left) and $A_{FB}$ (right) values as a function of $|\cos \theta_{\text{CMS}}^{D^{*+}}|$. Top plots are for $K_S^0 \pi^0$, middle plots for $K_S^0 \eta$, and bottom plots for $K_S^0 \eta'$ final states. The dashed curves show the leading-order prediction for $A_{FB}$.](image)
average over the \(|\cos\theta_{CMS}|\) bins is \(5.1/4\ (K^0_S\pi^0), 3.0/3\ (K^0_S\eta),\) or \(5.3/3\ (K^0_S\eta')\). The observed \(A_{CB}\) values decrease with \(\cos\theta_{CMS}\) as expected from the leading-order prediction [20]. The observed deviations from the prediction are expected due to higher order corrections. Similar \(A_{CB}\)'s were found in previous measurements [13, 14, 21]. The results are validated with toy pseudo-experiments and full detector simulation Monte Carlo events. We found no systematic deviations from the input values.

We consider several sources of systematic uncertainty. The uncertainty due to the limited size of the tagged and untagged samples was discussed above. To estimate the systematic uncertainty due to the choice of fitting method and parameters, we vary the histogram binnings, fitting intervals, and signal and background parameterizations. We also consider the systematic uncertainties due to the choice of \(\cos\theta_{CMS}\) binning. Finally, we include possible effects due to the differences in interactions of \(K^0\) and \(K^0\) mesons with the material of the detector as explained in Ref. [21], and assign a systematic uncertainty of 0.06% due to this effect. Table II summarizes the components of the systematic uncertainties. The larger uncertainties in \(A_{CP}^{K^0\ra K^0_S\eta}\) due to the choice of fitting method are a consequence of smaller statistics of these samples.

### TABLE II: Summary of systematic uncertainties in \(A_{CP}\)

| Source                  | \(K^0_S\) \(\pi^0\) (%) | \(K^0_S\) \(\eta\) (%) | \(K^0_S\) \(\eta'\) (%) |
|------------------------|--------------------------|-------------------------|-------------------------|
| \(A^T_{s}\) determination | 0.08                     | 0.08                    | 0.08                    |
| Fitting                | 0.02                     | 0.12                    | 0.10                    |
| \(\cos\theta_{CMS}\) binning | <0.01                   | 0.01                    | 0.03                    |
| \(K^0/K^0\)-material effects | 0.06                    | 0.06                    | 0.06                    |
| Total                  | 0.10                     | 0.16                    | 0.14                    |

From the total uncertainties shown in Table II we obtain \(A_{CP}^{D^0\ra K^0_S\pi^0} = (-0.28 \pm 0.19 \pm 0.10)\%\), \(A_{CP}^{D^0\ra K^0_S\eta} = (+0.54 \pm 0.51 \pm 0.16)\%\) and \(A_{CP}^{D^0\ra K^0_S\eta'} = (+0.98 \pm 0.67 \pm 0.14)\%\) where the first uncertainties are statistical and the second are systematic. Table III summarizes the results, current world average \(\tilde{6}\), and \(A_{CP}^{K^0}\).

### TABLE III: Summary of the \(A_{CP}\) measurements. The first uncertainties in the second column are statistical and the second are systematic. The third column shows the world average of \(A_{CP}\) and the fourth \(A_{CP}^{K^0}\). \(A_{CP}^{D^0\ra K^0_S\pi^0}\) are the first measurements, hence no world average of \(A_{CP}\) is given in the third column.

|                     | Belle (%) | Ref. [9] (%) | \(A_{CP}^{K^0}\) (%) |
|---------------------|-----------|-------------|----------------------|
| \(A_{CP}^{D^0\ra K^0_S\pi^0}\) | -0.28 \pm 0.19 \pm 0.10 | +0.1 \pm 1.3 | -0.332 \pm 0.006 |
| \(A_{CP}^{D^0\ra K^0_S\eta}\) | +0.54 \pm 0.51 \pm 0.16 | ---         | -0.332 \pm 0.006 |
| \(A_{CP}^{D^0\ra K^0_S\eta'}\) | +0.98 \pm 0.67 \pm 0.14 | ---         | -0.332 \pm 0.006 |

Besides the \(A_{CP}\) measurements listed in Table III, we test the universality of \(a_{ind}^{K^0}\) assuming negligible new \(CP\) violating effects in \(D^0\) decays to the \(K^0_S\pi^0\) final state as discussed in Ref. [6]. By subtracting \(A_{CP}^{K^0}\) from \(A_{CP}^{D^0\ra K^0_S\pi^0}\), we obtain \(a_{ind}^{K^0} = (+0.05 \pm 0.19 \pm 0.10)\%\), which is consistent with \(-A_C = (-0.01 \pm 0.30 \pm 0.15)\%\) obtained in Ref. [2]. This is the first experimental test of \(a_{ind}^{K^0}\) in \(D^0\) decays with a sensitivity near 0.3%. By averaging the two independent values we obtain \(a_{ind}^{K^0} = (+0.03 \pm 0.18)\%\), where the uncertainty includes the statistical and systematic errors, and represents the most precise value of \(a_{ind}^{K^0}\) from a single-experiment currently. Using the average \(a_{ind}^{K^0}\), we also update the values of \(a_{ind}^{D^0\ra K^0_S\pi^0}\) and \(a_{ind}^{D^0\ra \pi^+\pi^-}\) from Ref. [13], which are \((-0.46 \pm 0.37)\%\) and \((+0.40 \pm 0.56)\%\) [22], respectively. The errors include all the uncertainties of input measurements.

In summary, we report a search for \(CP\) violation in the decays \(D^0 \ra K^0_SP^0\) using a data sample with an integrated luminosity of 791 fb\(^{-1}\) collected with the Belle detector. We observe no evidence for \(CP\) violation. The measurement in the decay \(D^0 \ra K^0_S\pi^0\) is the most precise measurement of any \(CP\) asymmetry in the charmed particle sector to date. We also report the first measurements of \(CP\) asymmetries in the decays \(D^0 \ra K^0_S\eta\) and \(D^0 \ra K^0_S\eta'\). Our results are consistent with the SM and can be used to place the most stringent constraints on NP models arising from the measurements of \(CP\) violation in the charm sector at present.

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