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We search for CP violation in Cabibbo-suppressed charged D meson decays by measuring the difference between the CP violating asymmetries for the Cabibbo-suppressed decays $D^{\pm} \to K^+K^-\pi^{\pm}$ and the Cabibbo-favored decays $D_s^{\pm} \to K^+K^-\pi^{\pm}$ in the K^+K^- mass region of the ϕ resonance. Using 955 fb^{-1} of data collected with the Belle detector we obtain $A_{CP}^{D^+\to\phi\pi^+} = (+0.51 \pm 0.28 \pm 0.05)\%$. The measurement improves the sensitivity of previous searches by more than a factor of five. We find no evidence for direct CP violation.

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Studying CP asymmetries in D meson decays provides a promising opportunity to search for new physics (NP) beyond the Standard Model (SM) [1]. Here we study CP asymmetries in charged $D^+ \to \phi\pi^+$ and $D_s^+ \to \phi\pi^+$ decays [2]. The observable of interest is

$$A_{CP}^{D_{(s)}^+\to\phi\pi^+} = \frac{\Gamma(D_{(s)}^+ \to \phi\pi^+) - \Gamma(D_{(s)}^- \to \phi\pi^-)}{\Gamma(D_{(s)}^+ \to \phi\pi^+) + \Gamma(D_{(s)}^- \to \phi\pi^-)} , \quad (1)$$

where Γ is the partial decay width. This time-integrated asymmetry arises from CP violation (CPV) in decay amplitudes. Within the SM, CPV in D decay amplitudes is predicted to be very small. The largest effect occurs for singly Cabibbo-suppressed (SCS) decays such as $D^+ \to \phi\pi^+$, which are governed by the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements $V_{cs}V_{us}^*$. However, even for these decays A_{CP} is predicted to be only $\mathcal{O}(0.1\%)$ or less [3]. In contrast, several NP models predict A_{CP} to be as large as 1%. Experimentally, to cancel detector-induced asymmetries and other systematic effects, we measure the difference

$$\Delta A_{\rm rec} = \frac{N(D^+) - N(D^-)}{N(D^+) + N(D^-)} - \frac{N(D_s^+) - N(D_s^-)}{N(D_s^+) + N(D_s^-)} , \quad (2)$$

where the second term corresponds to the Cabibbo-favored (CF) decay $D_s^+ \to \phi\pi^+$. This CF decay is governed by the CKM matrix elements $V_{cs}V_{ud}^*$ and is expected to have negligible A_{CP} [4]; thus, a measurement of $\Delta A_{\rm rec}$ probes $A_{CP}^{D^+\to\phi\pi^+}$. Measuring a relatively large value would be interpreted as evidence for NP. Previously, CPV in D meson SCS decays has been searched for in several final states [5]. No significant asymmetries were found, with the best sensitivities ranging from $\mathcal{O}(0.2\%)$ to $\mathcal{O}(2\%)$ depending on the decay mode [6–8].

The measurement is based on 955 fb^{-1} of data recorded with the Belle detector [9] at the KEKB asymmetric-energy e^+e^- collider [10], which primarily operated at the center-of-mass (CM) energy of the $\Upsilon(4S)$ resonance and 60 MeV below. A fraction of the data was recorded at the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, and $\Upsilon(5S)$ resonances; these data are included in the measurement. The selected $D_{(s)}^+$ mesons for the measurement are primarily produced in the continuum events $e^+e^- \to c\bar{c}$. The Belle detector is described in detail elsewhere [9, 11]: in particular, it includes a silicon vertex detector (SVD), a central drift chamber, an array of aerogel Cherenkov counters, time-of-flight scintillation counters, an electromagnetic calorimeter and a muon detector.

We reconstruct the decays $D_{(s)}^+ \to \phi\pi^+$ in the $\phi \to K^+K^-$ decay mode. Each final state charged particle is required to have at least two associated SVD hits in each of the two measured coordinates. To select pion and kaon candidates, we impose standard particle identification criteria [12]. The identification efficiencies and the misidentification probabilities are about 90% and 5%, respectively. In addition, we require loose proton veto criteria for kaon candidates and loose lepton veto criteria for pion candidates, since we found that a considerable fraction of background (23%) involves misidentified protons and leptons. D meson daughter particles are refitted to a common vertex and the D meson candidate is constrained to originate from the e^+e^- interaction region. Confidence levels exceeding 10^{-3} are required for both fits. In order to reject D mesons produced in B meson decays, the D meson momentum in the e^+e^- CM system must satisfy $p_D^* > 2.5$ GeV/c, for the data taken below $\Upsilon(5S)$, and $p_D^* > 3.1$ GeV/c for the $\Upsilon(5S)$ data.

We accept candidates in the invariant mass regions of D and ϕ mesons, 1.80 GeV/$c^2 < M_{KK\pi} < 2.05$ GeV/c^2 and $M_{KK} < 1.07$ GeV/c^2. For the small fraction of events with multiple candidates (4.6%), we select a single best candidate: the one with the smallest χ^2 of the production and decay vertex fits.

We study background using a generic Monte Carlo (MC) simulation based on EVTGEN [13] and GEANT3 [14]. We find that the main component (97%) is the combinatorial background whose shape in $M_{KK\pi}$ can be fitted well with an exponential function. Other background components are mainly due to decays of charm particles and have a complicated structure in $M_{KK\pi}$. However, their fractions are sufficiently small that the structure is obscured by the statistical fluctuations of the main background component. The combinatorial background can be further divided into random combinations of a correctly reconstructed ϕ meson and a π^+ (42%), and the rest (58%).

To improve the purity of the D^+ and D_s^+ data sample we require: $|M_{KK} - m_\phi| < 16$ MeV/c^2, where m_ϕ is the nominal mass of ϕ, $p_\pi > 0.38$ GeV/c, where p_π is the laboratory momentum of π^+, and $|\cos\theta_{\rm hel}| > 0.28$, where $\theta_{\rm hel}$ is the angle between K^- and $D_{(s)}^+$ momenta in the rest frame of ϕ. These selection criteria are obtained by minimizing the expected statistical error on $\Delta A_{\rm rec}$ using signal and background samples from the generic MC simulation. The simulation has been tuned prior to running the optimization procedure to reproduce the mass resolutions of the D signals in data and the signal-to-background ratios of the data.

The measured asymmetry $A_{\rm rec}$ can be written as the sum of several contributions that are assumed to be small:

$$A_{\rm rec} = A_{CP} + A_{FB}(\cos\theta^*) + A_\epsilon^{KK} + A_\epsilon^\pi(p_\pi, \cos\theta_\pi). \quad (3)$$

In addition to the intrinsic asymmetry, A_{CP}, there is a forward-backward asymmetry (A_{FB}) in the production of D mesons in $e^+e^- \to c\bar{c}$ arising from $\gamma - Z^0$ interference and higher-order QED effects. This term is an odd function of the cosine of the D meson production polar angle θ^* in the CM system and could differ between D^+ and D_s^+ due to fragmentation effects. Furthermore, there are contributions due to asymmetry in the reconstruction efficiencies of oppositely charged kaons (A_ϵ^{KK}) and pions (A_ϵ^π). The term $A_\epsilon^{KK} \equiv 0$ for $\phi \to K^+K^-$ decays. However, the interference with other intermediate states in the decay $D_{(s)}^+ \to K^+K^-\pi^+$ introduces a small difference in momentum distributions of the same-sign and the opposite-sign kaons (where the sign is relative to the $D_{(s)}$ meson charge), as shown in Fig. 1. The difference in momentum distributions in combination with the kaon detection asymmetry A_ϵ^K leads to a non-zero A_ϵ^{KK}, as explained below.

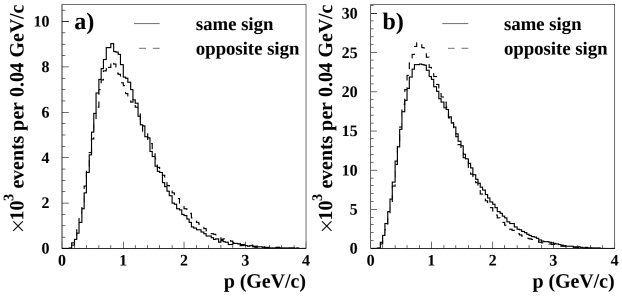

FIG. 1: Background subtracted momentum distributions of kaons of the same and opposite charges relative to that of the D meson: (a) for $D^\pm$ decays and (b) for $D_s^\pm$ decays. Background is taken from sidebands in $M_{KK\pi}$.

We denote the intrinsic laboratory phase space distribution of the kaon pair by $P(x_1, x_2)$, where $x_1 \equiv (p_1, \cos\theta_1)$ and $x_2 \equiv (p_2, \cos\theta_2)$ label the phase space variables of same-sign and opposite-sign kaons, respectively. The measured same-sign and opposite-sign single kaon distributions are obtained from the intrinsic $P(x_1, x_2)$ by:

$$P_{1(2)}(x_{1(2)}) = \frac{\epsilon(x_{1(2)}) \int P(x_1, x_2)\epsilon(x_{2(1)})dx_{2(1)}}{\int\int dx_1 dx_2 P(x_1, x_2)\epsilon(x_1)\epsilon(x_2)}, \quad (4)$$

where $\epsilon(x)$ is the phase-space dependent detection efficiency. The numbers of detected positively and negatively charged D mesons are

$$N^\pm = \int\int dx_1 dx_2 P(x_1, x_2)\epsilon_{K^\pm}(x_1)\epsilon_{K^\mp}(x_2), \quad (5)$$

where $\epsilon_{K^\pm}(x) = \epsilon(x)(1 \pm A_\epsilon^K(x))$ are the efficiencies of the $K^\pm$ as functions of kaon phase space x. From this and neglecting terms quadratic in A_ϵ^K one obtains:

$$A_\epsilon^{KK} = \int (P_1(x) - P_2(x)) A_\epsilon^K(x) dx, \quad (6)$$

where $P_1(x)$ and $P_2(x)$ are normalized distributions of the detected same-sign and opposite-sign kaons, respectively, given by Eq. (4) and the integration runs over the kaon phase space $x \equiv (p, \cos\theta)$.

The last term in Eq. (3) is a function of pion momentum and polar angle in the laboratory frame. In the difference of measured D^+ and D_s^+ asymmetries, provided the measurement is done in bins of the three-dimensional (3D) phase space $(\cos\theta^*, p_\pi, \cos\theta_\pi)$, the last term in Eq. (3) cancels,

$$\Delta A_{\rm rec} = A_{CP}^{D^+\to\phi\pi^+} + \Delta A_{FB}(\cos\theta^*) + \Delta A_\epsilon^{KK}. \quad (7)$$

In the above equation we assume that the intrinsic $A_{CP}^{D_s^+\to\phi\pi^+}$ is negligible, as discussed in the introduction. We use $10\times10\times10$ equal size bins of the 3D phase space with $p_\pi < 5$ GeV/c. The yields of D^+, D^-, D_s^+ and D_s^- decays are determined from a binned likelihood fit to the $M_{KK\pi}$ distributions in each sufficiently populated 3D bin. We require at least 100 entries in the histogram in order to perform the fit. To parameterize the non-Gaussian signal shape with as few parameters as possible, we use the distribution of pulls determined with MC simulation; the pulls are calculated as $(M_{KK\pi} - \overline{m})/\sigma_m$, where $\overline{m}$ and σ_m are the 3D bin-dependent mean and standard deviation of the D^+ or D_s^+ invariant mass distributions. The pull distribution is fitted with a sum of four Gaussians to obtain their fractions $f_i^{\rm pull}$, mean positions $x_i^{\rm pull}$ and the widths $\sigma_i^{\rm pull}$. The signal shape for the decays with no final state radiation (FSR) is parameterized with:

$$S_{4g}(x) = \sum_{i=1}^{4} \frac{f_i^{\rm pull}}{\sqrt{2\pi}s_i} e^{-\frac{(x-x_i^0)^2}{2s_i^2}}, \qquad (8)$$

where $s_i = \sigma_i^{\rm pull}\sigma$ and $x_i^0 = x_i^{\rm pull}\sigma_i^{\rm pull} + x_0$. The normalized shape given by Eq. (8) has two free varying parameters: the position x_0 and the width σ.

The pull distribution is found to be $\cos\theta^*$ dependent; it becomes asymmetric at the edges of $\cos\theta^*$ space. Thus, to improve the mass fits, we use $\cos\theta^*$ dependent pull parameters $f_i^{\rm pull}$, $x_i^{\rm pull}$ and $\sigma_i^{\rm pull}$ in Eq. (8), which are obtained from fits to simulated distributions in ten bins of $\cos\theta^*$.

The shape of the FSR tail $S_{\rm FSR}(x)$ and its fraction $p_{\rm FSR}$ [15] are taken from MC simulation using PHOTOS [16] to simulate FSR. The normalized signal shape is then $S(x) = (1 - p_{\rm FSR})S_{4g}(x) + p_{\rm FSR}S_{\rm FSR}(x)$. The background is parameterized with an exponential function of a quadratic polynomial, $B(x) = e^{a+bx+cx^2}$, with free parameters a, b, and c.

The parameterization of the $M_{KK\pi}$ distribution includes two signal peaks and the background, and has eight free varying parameters: two yields ($N_{D^\pm}$, $N_{D_s^\pm}$), two peak positions ($m_{D^\pm}$, $m_{D_s^\pm}$), the width of $D^\pm$ peak ($\sigma_{D^\pm}$) and three background parameters (a, b, c). The ratio of the $D_s^\pm$ and $D^\pm$ peak widths, $f = \sigma_{D_s^\pm}/\sigma_{D^\pm}$, is fixed from MC simulation in order to ensure stable fitting.

Of the approximately 700 sufficiently populated invariant mass distributions ($D_{(s)}^+$ and $D_{(s)}^-$ per each 3D bin), 658 are fitted successfully. The quality of fits is good: the mean of the normalized χ^2 distribution is 1.000 and the r.m.s is 0.090 for 242 degrees of freedom; the corresponding confidence level distribution is uniform. From the fitted yields in 3D bins we calculate the D^+ and D_s^+ asymmetries, and the asymmetry differences $\Delta A_{\rm rec}$. We consider only those bins in which the yield has a significance greater than 3σ; this requirement must be fulfilled

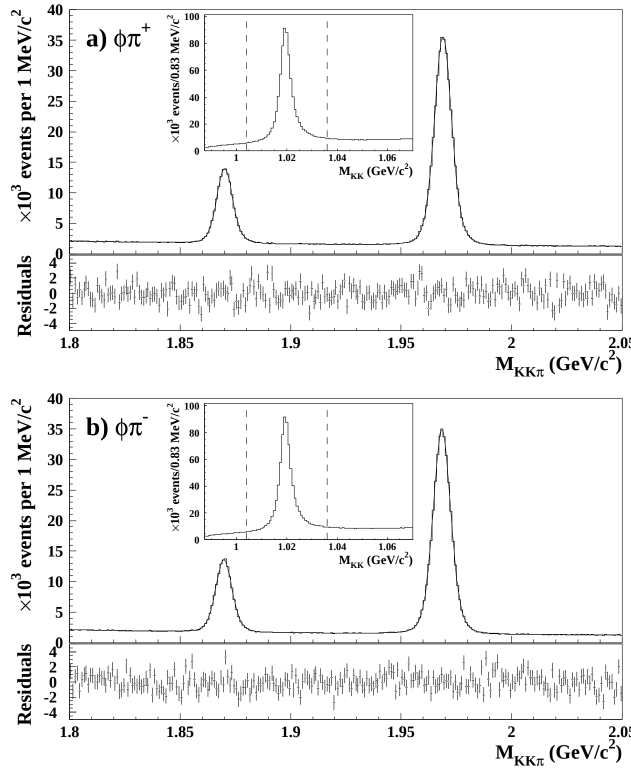

FIG. 2: Sum of invariant mass distributions with the sum of fitted functions superimposed for (a) positively and (b) negatively charged D mesons. The plots beneath the distributions show the residuals. The inserts show the corresponding M_{KK} distribution; the selected region is marked with the dashed lines.

for all four measured yields in a bin. The sum of mass distributions in these bins is shown in Fig. 2. We find 237525 ± 577 $D^\pm$ and 722871 ± 931 $D_s^\pm$ decays. The residuals of the sum of all the successfully fitted distributions do not show any significant structure.

The asymmetry difference in each bin is then corrected with ΔA_ϵ^{KK} for that bin:

$$\Delta A_{\rm rec}^{\rm cor} = \Delta A_{\rm rec} - \Delta A_\epsilon^{KK}. \qquad (9)$$

The corrections are determined using Eq. (6) and the experimental data for the $P_1(x)$ and $P_2(x)$ distributions. In particular, we calculate A_ϵ^{KK} for events in the signal window, $m_D \pm 15$ MeV/c^2, and subtract the asymmetry for events in an equal width sideband displaced ± 20 MeV/c^2 from the nominal D meson mass m_D.

The kaon asymmetry A_ϵ^K, which is needed in Eq. (6), is measured using $D_s^+ \to \phi\pi^+$ and $D^0 \to K^-\pi^+$ decays; for the latter decay the measured asymmetry can be expressed as $A_{\rm rec} = A_{CP} + A_{FB} - A_\epsilon^K + A_\epsilon^\pi$. By assuming negligible CP violation (both are CF decays) and the same forward-backward asymmetry, and by neglecting the A_ϵ^{KK} term in Eq. (3), the difference of measured asymmetries is equal to A_ϵ^K [17].

The procedure is similar to that used in [6]. First we determine the asymmetry of $D_s^+ \to \phi\pi^+$ in 3D bins using the fitted yields. This asymmetry map is used to weight $D^0 \to K^-\pi^+$ events in order to determine the $D^0/\overline{D}^0$ corrected yields in bins of the kaon phase space. The yields are obtained by the sideband subtraction method as in [8]. The kaon asymmetry map is then calculated from the corrected $D^0/\overline{D}^0$ yields in the range $0 < p_K < 4$ GeV/c and $-1 < \cos\theta_K < 1$ divided into 10×10 equal size bins.

The following corrections are obtained with Eq. (6) for the total 3D phase space: $A_\epsilon^{KK} = (+0.060 \pm 0.013)\%$ for D^+ and $A_\epsilon^{KK} = (-0.051 \pm 0.012)\%$ for D_s^+, which yields $\Delta A_\epsilon^{KK} = (+0.111 \pm 0.025)\%$. The reason for a non-zero value is the opposite sign of momentum asymmetries in D^+ and D_s^+ decays, as shown in Fig. 1. The uncertainties are due to statistical variations of A_ϵ^K and $P_1(x) - P_2(x)$; the error on ΔA_ϵ^{KK} is included in the systematic uncertainty.

The corrected asymmetry differences in 3D bins, $\Delta A_{\rm rec}^{\rm cor}$ defined by Eq. (9), are used to calculate error-weighted averages in bins of $\cos\theta^*$; error-weighted averages are obtained with the least squared fit. Finally, $A_{CP}^{D^+\to\phi\pi^+}$ and ΔA_{FB} are extracted by adding/subtracting the asymmetry difference in opposite bins of $\cos\theta^*$:

$$A_{CP}^{D^+\to\phi\pi^+} = \frac{\Delta A_{\rm rec}^{\rm cor}(\cos\theta^*) + \Delta A_{\rm rec}^{\rm cor}(-\cos\theta^*)}{2}, \quad (10)$$

$$\Delta A_{FB} = \frac{\Delta A_{\rm rec}^{\rm cor}(\cos\theta^*) - \Delta A_{\rm rec}^{\rm cor}(-\cos\theta^*)}{2}. \quad (11)$$

The results are shown in Fig. 3. By fitting the data points of Fig. 3a with a constant we obtain $A_{CP}^{D^+\to\phi\pi^+} = (0.51 \pm 0.28)\%$, where the error is statistical only. The result is consistent with zero within 1.8 standard deviations.

Figure 3b shows the difference in forward-backward asymmetries. The χ^2 test with respect to $\Delta A_{FB} = 0$ gives $\chi^2/\text{ndf} = 10.57/5$, which corresponds to a confidence level of 6%; no significant difference is found between the forward-backward asymmetries for D^+ and D_s^+. A fit to a constant yields a value of $\Delta A_{FB} = (0.25 \pm 0.28(stat.))\%$.

We consider five significant sources of systematic uncertainties (Table I). As discussed before, the A_ϵ^{KK} corrections are uncertain to 0.025%. The impact of 3D binning is studied by changing the binning from 10×10×10 bins to 20×10×10, 10×20×10 and 10×10×20 bins; we obtain a 0.026% variation in $A_{CP}^{D^+\to\phi\pi^+}$. By doubling the number of bins in the invariant mass histograms a variation of 0.022% is obtained. The impact of signal parameterization is studied by replacing the four-Gaussian shape with a triple Gaussian shape and the impact of background parameterization is studied by replacing the default parameterization with a simple exponential function. We also vary the range in which we fit the distributions; all these changes give a 0.013% variation in the result. The uncertainty of the width ratio f, which is fixed in the fit, propagates into a 0.012% uncertainty in the result. By adding the last two numbers in quadrature we obtain an estimate of 0.018% for the systematic uncertainty of the fitting procedure. The last source is the selection of fit results; by changing the requirement from $N/\sigma_N > 3$ to $N/\sigma_N > 5$ we obtain a 0.020% variation in the result. We estimate the total systematic uncertainty by summing individual contributions in quadrature and obtain 0.050%.

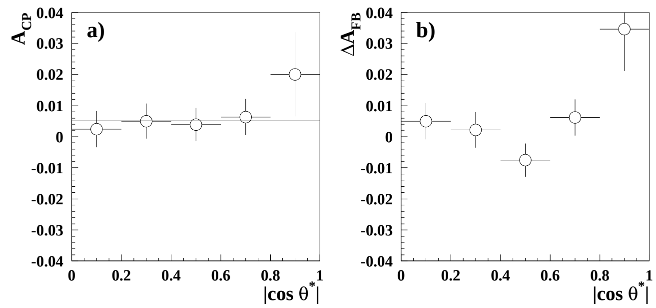

FIG. 3: CP-violating asymmetry (a) and forward-backward asymmetry difference (b) in bins of $|\cos\theta^*|$. The horizontal line in (a) is a constant fit to the data points.

TABLE I: Summary of systematic uncertainties in $A_{CP}^{D^+\to\phi\pi^+}$

Source	Uncertainty (%)
A_ϵ^{KK} corrections	0.025
3D binning	0.026
Invariant mass binning	0.022
Fitting procedure	0.018
Selection of fit results	0.020
Sum in quadrature	0.050

In summary, we searched for CP violation in the decays $D^+ \to \phi\pi^+$ by measuring the CP violating asymmetry difference between Cabibbo-suppressed (D^+) and Cabibbo-favored (D_s^+) decays in a mass region around the ϕ resonance, $m_\phi \pm 16$ MeV/c^2. In this mass region the decays $D^+ \to \phi\pi^+$ are dominant ($> 90\%$). We have made no attempt to disentangle the ϕ from other intermediate resonances. Using 955 fb^{-1} of experimental data collected with the Belle detector and assuming negligible CPV in CF decays we measure:

$$A_{CP}^{D^+\to\phi\pi^+} = (+0.51 \pm 0.28 \pm 0.05)\%. \quad (12)$$

The result shows no evidence for CP violation and agrees with SM predictions. Previously, the most precise measurements were from CLEO [18] and BaBar [19]; our measurement improves the precision by more than a factor of five. We also measure for the first time the difference in the forward-backward asymmetries of D^+ and D_s^+ mesons and find no significant deviation from zero.

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