Studies of the Decay $B^{\pm} \to D_{CP}K^{\pm}$

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We report studies of the Cabibbo-suppressed decay $B^{\pm} \to D_{CP}K^{\pm}$, where D_{CP} denotes CP eigenstates of the $D^0 - \bar{D}^0$ system. The analysis is based on a 29.1 fb^{-1} sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric e^+e^- storage ring. We measure ratios of branching fractions, relative to Cabibbo-favored $B^{\pm} \to D_{CP}\pi^{\pm}$, of $\mathcal{B}(B^- \to D_1K^-)/\mathcal{B}(B^- \to D_1\pi^-) = 0.125 \pm 0.036 \pm 0.010$ and $\mathcal{B}(B^- \to D_2K^-)/\mathcal{B}(B^- \to D_2\pi^-) = 0.119 \pm 0.028 \pm 0.006$; the index 1 (2) denotes the $CP = +1$ (-1) eigenstate. We also extract the partial rate asymmetries for $B^{\pm} \to D_{CP}K^{\pm}$, finding $\mathcal{A}_1 = 0.29 \pm 0.26 \pm 0.05$ and $\mathcal{A}_2 = -0.22 \pm 0.24 \pm 0.04$.

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Direct CP violation in $B^{\pm} \to D_{CP}K^{\pm}$ decay, where D_{CP} denotes neutral D mesons that decay to CP eigenstates, provides a promising way to extract the angle ϕ_3 of the Cabibbo-Kobayashi-Maskawa (CKM) unitarity triangle [1,2]. A partial rate asymmetry $\mathcal{A}_{CP}$ between the $D_{CP}K^-$ and $D_{CP}K^+$ final states can arise from interference between $b \to c$ and $b \to u$ processes. The relation of $\mathcal{A}_{CP}$ and the ϕ_3 angle [3] is given by

$$\mathcal{A}_{1,2} \equiv \frac{\mathcal{B}(B^- \to D_{1,2}K^-) - \mathcal{B}(B^+ \to D_{1,2}K^+)}{\mathcal{B}(B^- \to D_{1,2}K^-) + \mathcal{B}(B^+ \to D_{1,2}K^+)} = \frac{2r\sin\delta'\sin\phi_3}{1 + r^2 + 2r\cos\delta'\cos\phi_3}, \quad (1)$$

where indices 1 and 2 denote the $CP = +1$ and $CP = -1$ eigenstates of the neutral D mesons, r is the ratio of the amplitudes, $r \equiv |A(B^- \to \bar{D}^0K^-)/A(B^- \to D^0K^-)|$, and δ' is the strong phase difference between the two amplitudes, with $\delta' = \delta$ for D_1 and $\delta' = \delta + \pi$ for D_2. This asymmetry can have a nonzero value when both ϕ_3 and δ are nonzero. In principle, one can constrain the angle ϕ_3 from the measurement of asymmetries $\mathcal{A}_{1,2}$.

$B \to DK$ processes have been studied by measuring the ratio of the Cabibbo-suppressed process $B^- \to D^0K^-$ to the Cabibbo-favored process $B^- \to D^0\pi^-$. Belle [4] measured $R = \mathcal{B}(B^- \to D^0K^-)/\mathcal{B}(B^- \to D^0\pi^-) = 0.079 \pm 0.009 \pm 0.006$, while CLEO [5] reported $R = 0.055 \pm 0.014 \pm 0.005$. Both measurements are in agreement with the naïve theoretical expectation: assuming factorization, $R = \tan^2\theta_C(f_K/f_\pi)^2 \approx 0.074$ in a tree-level approximation, where θ_C is the Cabibbo angle, and f_K and f_π are the decay constants.

In this Letter, we report the first measurement of $B^{\pm} \to D_{CP}K^{\pm}$ decay. We also give a comparison of the ratio of branching fractions R for the flavor specific state and the $CP = \pm 1$ eigenstates, and a determination of the

asymmetries $\mathcal{A}_{1,2}$. The results are based on a 29.1 fb^{-1} data sample collected on the $\Upsilon(4S)$ resonance with the Belle detector [6] at the KEKB asymmetric e^+e^- collider [7], corresponding to approximately 31.3×10^6 $B\bar{B}$ events. The inclusion of charge conjugate decay modes is implied throughout this Letter unless otherwise stated.

Belle is a general-purpose detector with a 1.5 T superconducting solenoid magnet that can distinguish the Cabibbo-suppressed (-favored) processes $B^- \to D^0K^-$ ($D^0\pi^-$) by means of particle identification and kinematic separation. A detailed description of the Belle detector can be found elsewhere [6].

We distinguish the processes $B^- \to D^0h^-$, $h^- = K^-, \pi^-$, using particle identification of the prompt hadron h^- and the effect of the mass difference at the final stage of event selection. The decay $B^- \to D^0\pi^-$ is used as a control sample to establish constraints on kinematic variables, resolution of detectors, evaluation of systematic uncertainties, and normalization of results.

Flavor specific D^0 meson candidates (denoted D_f) are reconstructed via $D^0 \to K^-\pi^+$; for $CP = +1$ eigenstates we use $D_1 \to K^-K^+$ and $\pi^-\pi^+$ and for $CP = -1$ we use $D_2 \to K_S\pi^0$, $K_S\omega$, $K_S\phi$, $K_S\eta$, and $K_S\eta'$.

$K_S \to \pi^+\pi^-$ candidates are reconstructed from oppositely charged tracks with an invariant mass within $\pm 3\sigma$ of the nominal K_S mass. We impose a photon energy cut $E_\gamma > 30$ MeV to reconstruct $\pi^0 \to \gamma\gamma$, and require an invariant mass within $\pm 3\sigma$ of the nominal value. $\eta \to \gamma\gamma$ and $\eta' \to \eta\pi^+\pi^-$ candidates are reconstructed using mass cuts $0.495\ \mathrm{GeV}/c^2 < M(\gamma\gamma) < 0.57\ \mathrm{GeV}/c^2$ and $0.904\ \mathrm{GeV}/c^2 < M(\eta\pi^+\pi^-) < 1.003\ \mathrm{GeV}/c^2$, and a momentum cut $p_\eta > 500\ \mathrm{MeV}/c$.

Vector meson decays $\omega \to \pi^+\pi^-\pi^0$ and $\phi \to K^+K^-$ are reconstructed requiring $0.733\ \mathrm{GeV}/c^2 < M(\pi^+\pi^-\pi^0) < 0.819\ \mathrm{GeV}/c^2$ and $1.007\ \mathrm{GeV}/c^2 < M(K^+K^-) < 1.031\ \mathrm{GeV}/c^2$; a helicity angle cut $|\cos\theta_{\mathrm{hel}}| > 0.4$ reduces the nonresonant $D^0 \to K_S\pi^+\pi^-\pi^0$ and $K_SK^+K^-$ backgrounds to a negligible level [8]. For $D^0 \to K_S\omega$, the $D^0 \to K^{*-}\rho^+$ background is rejected by vetoing $K_S\pi^-$ combinations within $\pm 75\ \mathrm{MeV}/c^2$ of the nominal K^* mass.

For each charged track, the particle identification system is used to determine likelihoods $\mathcal{L}_K$, $\mathcal{L}_\pi$, and the K/π likelihood ratio $P(K/\pi) = \mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi)$ [6]. We identify pions using $P(K/\pi) < 0.7$ for $D^0 \to K^-\pi^+$ and $\pi^-\pi^+$; kaons are required to satisfy $P(K/\pi) > 0.3$ for $D^0 \to K^-\pi^+$ and $P(K/\pi) > 0.7$ for $D^0 \to K^-K^+$. Pions from $D^0 \to \pi^-\pi^+$ are required to have momentum $p > 0.8\ \mathrm{GeV}/c$, and the D^0 candidate is vetoed if either pion, when combined with any other track in the event, has an invariant mass within $\pm 50\ \mathrm{MeV}/c^2$ of the nominal J/ψ mass, or $\pm 20\ \mathrm{MeV}/c^2$ of the nominal D^0 mass.

Candidate D^0 mesons are also required to have an invariant mass within $\pm 2.5\sigma$ of the nominal value, where σ is the measured mass resolution, which ranges from 5 to 18 MeV/c^2, depending on the decay channel. To improve the momentum determination, tracks and photons from the D^0 candidate final states, except for $K_S\pi^0$, $K_S\eta$, and $K_S\eta'$, are then refitted according to the nominal D^0 mass hypothesis and the reconstructed vertex position.

We analyze $B^- \to DK^-$ and $D\pi^-$ events using the variables ΔE and M_{lc}. The energy difference in the center of mass frame (c.m.) is calculated by assigning the pion mass to the prompt hadron h^-: $\Delta E = E_D^{\mathrm{c.m.}} + E_{h^-}^{\mathrm{c.m.}} - E_{\mathrm{beam}}^{\mathrm{c.m.}}$. The laboratory constrained mass is the B candidate mass calculated from laboratory momenta, assuming $e^+e^- \to B\bar{B}$: $M_{lc} = \sqrt{(E_B^{\mathrm{lab}})^2 - (p_B)^2}$, where $E_B^{\mathrm{lab}} = \frac{1}{E_{ee}}(s/2 + \mathbf{p}_{ee} \cdot \mathbf{p}_B)$, $\mathbf{p}_B$ is the laboratory momentum of the B meson candidate ($p_B = |\mathbf{p}_B|$), $\mathbf{p}_{ee}$ and E_{ee} are the laboratory momentum and energy of the e^+e^- system, and s is the square of the c.m. energy. We accept B candidates with $5.27\ \mathrm{GeV}/c^2 < M_{lc} < 5.29\ \mathrm{GeV}/c^2$.

Background events from $e^+e^- \to q\bar{q}$ continuum processes are rejected using event shape variables that distinguish between spherical $B\bar{B}$ events and jetlike continuum events. We construct a Fisher discriminant, $\mathcal{F} = \sum_{l=2,4} \alpha_l R_l^{so} + \sum_{l=1}^{4} \beta_l R_l^{oo}$, where α_l, β_l are coefficients maximizing discrimination between $B\bar{B}$ and continuum events, and R_l^{so}, R_l^{oo} are modified Fox-Wolfram moments [9]. We also use the angle θ_B between the beam axis and the c.m. momentum of the B meson. A likelihood variable is formed from the probability density functions of $\mathcal{F}$ and $\cos\theta_B$, for the signal ($\mathcal{L}_{\mathrm{sig}}$) and the continuum background ($\mathcal{L}_{\mathrm{cont}}$); we then apply cuts on the likelihood ratio $\mathcal{LR} = \mathcal{L}_{\mathrm{sig}}/(\mathcal{L}_{\mathrm{sig}} + \mathcal{L}_{\mathrm{cont}})$. Since each D^0 decay mode has different backgrounds, we optimize the $\mathcal{LR}$ cut for each mode by maximizing $S/\sqrt{S+N}$, where S (N) denotes the number of signal (background) events estimated by a Monte Carlo simulation [10]. For example, for the $D^0 \to K^-\pi^+$ mode, we require $\mathcal{LR} > 0.4$, retaining 87.1% of signal and 26.4% of the continuum background.

We use particle identification information on the prompt hadron to divide the remaining events into samples enriched in $B^- \to D^0K^-$ [$P(K/\pi) > 0.8$], and $B^- \to D^0\pi^-$ [$P(K/\pi) < 0.8$]. The ΔE distribution is then used to distinguish between $B^- \to D^0K^-$ (peaking at -49 MeV) and $B^- \to D^0\pi^-$ (peaking at 0 MeV), as shown in Fig. 1. In the $B^- \to D^0K^-$ enriched sample a second peak near $\Delta E = 0$ MeV, due to misidentified pions from $B^- \to D^0\pi^-$, can be seen in Figs. 1(b), 1(d), and 1(f)

The numbers of $B^- \to D^0\pi^-$ and $B^- \to D^0K^-$ events are extracted by fitting double Gaussian functions with different central values and widths to the ΔE distribution. Backgrounds originate from $q\bar{q}$ continuum events and $B\bar{B}$ events. Continuum events are distributed over the entire ΔE region, and the shape of this background is determined by fitting a linear function to

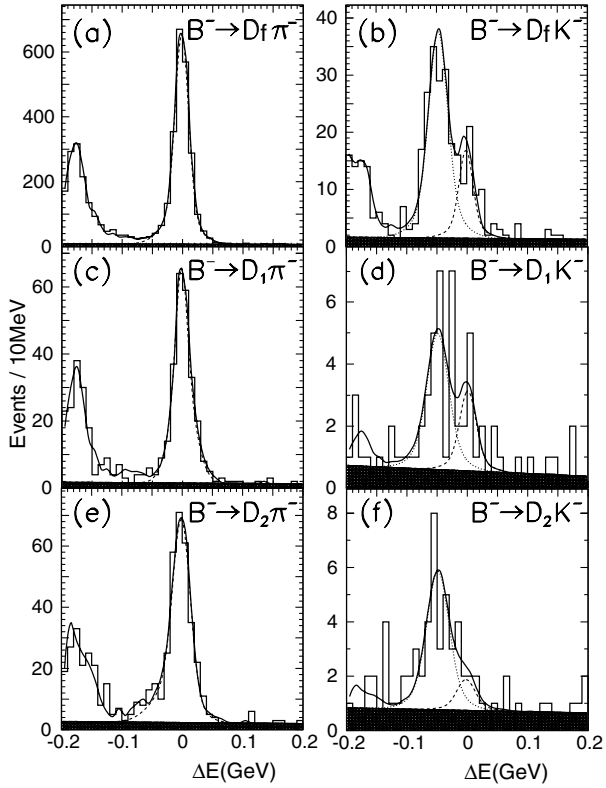

FIG. 1. ΔE distributions for $B^- \to D^0\pi^-/K^-$ candidates and fit results: (a) $B^- \to D_f\pi^-$, (b) $B^- \to D_fK^-$, (c) $B^- \to D_1\pi^-$, (d) $B^- \to D_1K^-$, (e) $B^- \to D_2\pi^-$, and (f) $B^- \to D_2K^-$, where in each case the pion mass is assigned to the prompt π^-/K^-. Dotted (dashed) lines show the distributions of $DK(D\pi)$ signals. The shaded plot shows the continuum background and the remaining component from $B\bar{B}$ background is estimated and fitted by Monte Carlo simulation. In the DK plots, the dashed curves show the $D^0\pi$ feed-across.

the ΔE distribution in the M_{lc} sideband region ($5.20\ \mathrm{GeV}/c^2 < M_{lc} < 5.26\ \mathrm{GeV}/c^2$). $B\bar{B}$ backgrounds, such as $B^- \to D^0\rho^-$ and $B^- \to D^*\pi^-$ processes, are mostly seen at negative values of ΔE; MC simulations are used to obtain the shape of their distribution.

In the fits to the $B^- \to D^0\pi^-$ enriched ΔE distribution, the signal peak position and width, and the normalization of continuum and $B\bar{B}$ backgrounds are free parameters. In the fits to the $B^- \to D^0K^-$ enriched sample, we calibrate the shape parameters of the $B^- \to D^0K^-$ double Gaussian using the $B^- \to D^0\pi^-$ data, following the procedure described in [4]: the $B^- \to D^0\pi^-$ distribution is fitted using a kaon mass hypothesis for the prompt pion, and the relative peak position is then reversed with respect to the origin. This accounts for the kinematical shifts and smearing of the ΔE peaks caused by the incorrect mass assignment. The shape parameters for the feed-across from $B^- \to D^0\pi^-$ are fixed using the fit results of the $B^- \to D^0\pi^-$ enriched sample.

The fit results are shown as solid curves in Fig. 1. The statistical significance of both D_1K^- and D_2K^- signals, defined as $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\max})}$, is over 5.0σ. ($\mathcal{L}_{\max}$ is the maximum likelihood in the ΔE fit and $\mathcal{L}_0$ is the likelihood when the signal yield is constrained to be zero.) The results are summarized in Table I.

The ratio of branching fractions is determined using

$$R = \frac{N(B^- \to D^0K^-)}{N(B^- \to D^0\pi^-)} \times \frac{\eta(B^- \to D^0\pi^-)}{\eta(B^- \to D^0K^-)} \times \frac{\epsilon(\pi)}{\epsilon(K)}, \quad (2)$$

where N is the number of events obtained, η is the signal detection efficiency, and ϵ is the prompt hadron identification efficiency. The signal detection efficiencies are determined from MC simulation: $\eta(B^- \to D^0K^-)$ is approximately 5% lower than $\eta(B^- \to D^0\pi^-)$ due to kaon decays in flight. Particle identification efficiencies $\epsilon(K)$, $\epsilon(\pi)$ are determined from a kinematically selected sample of $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ decays, using tracks in the same c.m. momentum ($p^{\mathrm{c.m.}}$) and polar angle regions as prompt hadrons from $B^- \to Dh^-$ decay ($2.1\ \mathrm{GeV}/c < p^{\mathrm{c.m.}} < 2.5\ \mathrm{GeV}/c$). For $P(K/\pi) > 0.8$, we find $\epsilon(K) = 0.778 \pm 0.005$ with a pion misidentification rate of 0.024 ± 0.002; $P(K/\pi) < 0.8$ gives a pion identification efficiency $\epsilon(\pi) = 0.972 \pm 0.007$.

Since the kinematics of the $B^- \to D^0K^-$ and $B^- \to D^0\pi^-$ processes are similar, the systematic uncertainties from detection efficiencies cancel in the ratios of

TABLE I. Results of fits for the $D^0\pi^-$ and D^0K^- decay modes. The event yields, the feed-across from $D^0\pi^-$ to the D^0K^- signal region, statistical significance of D^0K^- signals, efficiencies, and branching fraction ratios (R) are given. Efficiencies are determined by weighting according to the measured subcomponents [$\eta \equiv \sum_i \eta_i \mathcal{B}(D^0 \to X_i)$]. The results with the dominant decay mode of $D_{1,2}$ are also shown in parentheses.

	$B^- \to D^0K^-$ events	$B^- \to D^0\pi^-$ feed-across	Stat. sig.	$B^- \to D^0\pi^-$ events	Efficiency (%) $\eta(D^0\pi^-)/\eta(D^0K^-)$	Branching fraction ratio R
$B^- \to D_fh^-$	161.7 ± 14.5	51.3 ± 9.7	16.9	2245.1 ± 51.0	1.703/1.639	$0.094 \pm 0.009 \pm 0.007$
$B^- \to D_1h^-$	22.9 ± 6.1	9.6 ± 4.4	5.1	240.1 ± 16.7	0.173/0.165	$0.125 \pm 0.036 \pm 0.010$
$(D_1 \to K^-K^+)$	(18.9 ± 5.2)	(9.0 ± 3.7)		(202.0 ± 14.8)	(0.142/0.136)	(0.122 ± 0.035)
$B^- \to D_2h^-$	26.1 ± 6.5	4.9 ± 4.1	5.5	290.6 ± 19.1	0.184/0.173	$0.119 \pm 0.028 \pm 0.006$
$(D_2 \to K_S\pi^0)$	(14.8 ± 4.7)	(1.0 ± 2.2)		(171.5 ± 13.9)	(0.119/0.113)	(0.114 ± 0.037)

TABLE II. Summary of measured partial rate asymmetries.

Mode	$N(B^+)$	$N(B^-)$	$\mathcal{A}_{CP}$	90% C.L.
$B^\pm \to D_f K^\pm$	80.6 ± 10.1	81.1 ± 10.4	$0.003 \pm 0.089 \pm 0.037$	$-0.15 < \mathcal{A}_f < 0.16$
$B^\pm \to D_1 K^\pm$	8.1 ± 3.9	14.7 ± 4.6	$0.29 \pm 0.26 \pm 0.05$	$-0.14 < \mathcal{A}_1 < 0.73$
$B^\pm \to D_2 K^\pm$	16.4 ± 5.5	10.6 ± 4.2	$-0.22 \pm 0.24 \pm 0.04$	$-0.62 < \mathcal{A}_2 < 0.18$

branching fractions. The dominant systematic errors are the uncertainties in the shapes of backgrounds in the ΔE distributions (5.1%–7.9%), which are determined by varying the background shape of the fitting function by $\pm 1\sigma$, and K/π identification efficiencies (1.2%). The sum of the uncertainties for each mode are combined in quadrature to determine the total systematic errors for the ratios.

The resulting measurements of R are listed with their statistical and systematic errors in Table I. These are the first observations of the decays $B^- \to D_{CP}K^-$. As a check, the result for the flavor specific decay $B^- \to D_f h^-$ is listed as well, and is found to be consistent with previous measurements. We find no deviation of the R ratio for the $B^- \to D_{CP}K^-$ processes from the corresponding flavor specific modes beyond statistical errors.

To search for direct CP violation, we measure the partial rate asymmetries $\mathcal{A}_{1,2}$ in $B^\pm \to D_{1,2}K^\pm$ decays, fitting the B^+ and B^- yields separately for each mode. The results are shown in Table II. To construct 90% confidence intervals in $\mathcal{A}$, we combine statistical and systematic errors in quadrature, and assume that the total error is distributed as a Gaussian. We find $-0.14 < \mathcal{A}_1 < 0.73$ and $-0.62 < \mathcal{A}_2 < 0.18$, consistent with zero asymmetry. We also measure $\mathcal{A}$ for the flavor specific mode, and find a result consistent with zero, as expected.

The main sources of systematic errors for the partial rate asymmetries $\mathcal{A}$ are possible asymmetries in the measured background (1.5% − 3.9%), intrinsic asymmetry in the Belle detector (3.6%), and kaon identification (1.0%). We observe 1154.6 ± 35.4 $B^+ \to \bar{D}^0\pi^+$, $\bar{D}^0 \to K^+\pi^-$, and 1073.5 ± 34.5 $B^- \to D^0\pi^-$, $D^0 \to K^-\pi^+$ candidates, consistent with our expectation that the detector has no significant intrinsic charge asymmetry. Using MC simulation, we find that the contribution of nonresonant contaminations ($\sim$0.1%) of ω and ϕ can be neglected.

In conclusion, using 29.1 fb^{-1} of data collected with the Belle detector, we report studies of the decays $B^\pm \to D_{CP}K^\pm$. The ratios of branching fractions R for the decays $B^- \to D_{CP}K^-$ and $B^- \to D_{CP}\pi^-$ are consistent with that for the flavor specific decay within errors. The partial rate asymmetries $\mathcal{A}_{1,2}$ are consistent with zero within large errors. This is the first stage of a program to measure the angle ϕ_3 in the CKM unitarity triangle.

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