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Measurement of branching fraction ratios and CP asymmetries in $B^{\pm}\to D_{CP}K^{\pm}$

S. K. Swain,[7] T. E. Browder,[7] K. Abe,[8] T. Abe,[44] I. Adachi,[8] H. Aihara,[45] M. Akatsu,[22] Y. Asano,[50] T. Aso,[49] T. Aushev,[12] S. Bahinipati,[4] A. M. Bakich,[40] Y. Ban,[33] E. Banas,[27] A. Bay,[18] P. K. Behera,[51] I. Bizjak,[13] A. Bondar,[1] A. Bozek,[27] M. Bračko,[20,13] B. C. K. Casey,[7] M.-C. Chang,[26] Y. Chao,[26] K.-F. Chen,[26] B. G. Cheon,[39] R. Chistov,[12] S.-K. Choi,[6] Y. Choi,[39] Y. K. Choi,[39] M. Danilov,[12] L. Y. Dong,[10] J. Dragic,[21] A. Drutskoy,[12] S. Eidelman,[1] V. Eiges,[12] Y. Enari,[22] F. Fang,[7] A. Garmash,[1,8] T. Gershon,[8] B. Golob,[19,13] R. Guo,[24] J. Haba,[8] T. Hara,[31] H. Hayashii,[23] M. Hazumi,[8] I. Higuchi,[44] T. Higuchi,[8] L. Hinz,[18] T. Hokuue,[22] Y. Hoshi,[43] W.-S. Hou,[26] H.-C. Huang,[26] T. Iijima,[22] K. Inami,[22] A. Ishikawa,[22] R. Itoh,[8] H. Iwasaki,[8] Y. Iwasaki,[8] H. K. Jang,[38] J. H. Kang,[54] J. S. Kang,[15] P. Kapusta,[27] N. Katayama,[8] H. Kawai,[2] N. Kawamura,[55] T. Kawasaki,[29] H. Kichimi,[8] D. W. Kim,[39] H. J. Kim,[54] Hyunwoo Kim,[15] J. H. Kim,[39] S. K. Kim,[38] K. Kinoshita,[4] S. Kobayashi,[36] S. Korpar,[20,13] P. Križan,[19,13] P. Krokovny,[1] R. Kulasiri,[4] S. Kumar,[32] A. Kuzmin,[1] J. S. Lange,[5,35] G. Leder,[11] S. H. Lee,[38] J. Li,[37] A. Limosani,[21] S.-W. Lin,[26] D. Liventsev,[12] J. MacNaughton,[11] F. Mandl,[11] H. Matsumoto,[29] T. Matsumoto,[47] A. Matyja,[27] W. Mitaroff,[11] H. Miyata,[29] J. Mueller,[8] T. Nagamine,[44] Y. Nagasaka,[9] E. Nakano,[30] M. Nakao,[8] H. Nakazawa,[8] J. W. Nam,[39] Z. Natkaniec,[27] S. Nishida,[16] O. Nitoh,[48] T. Nozaki,[8] S. Ogawa,[42] T. Ohshima,[22] T. Okabe,[22] S. Okuno,[14] S. L. Olsen,[7] W. Ostrowicz,[27] H. Ozaki,[8] P. Pakhlov,[12] H. Palka,[27] C. W. Park,[15] H. Park,[17] K. S. Park,[39] L. S. Peak,[40] J.-P. Perroud,[18] M. Peters,[7] L. E. Piilonen,[52] M. Rozanska,[27] H. Sagawa,[8] Y. Sakai,[8] T. R. Sarangi,[51] M. Satapathy,[51] A. Satpathy,[8,4] O. Schneider,[18] J. Schümann,[26] A. J. Schwartz,[4] T. Seki,[47] S. Semenov,[12] K. Senyo,[22] R. Seuster,[7] M. E. Sevior,[21] T. Shibata,[29] H. Shibuya,[42] B. Shwartz,[1] J. B. Singh,[32] N. Soni,[32] S. Stanič,[8,*] M. Starič,[13] A. Sugi,[22] A. Sugiyama,[22] K. Sumisawa,[8] T. Sumiyoshi,[47] K. Suzuki,[8] S. Suzuki,[53] S. Y. Suzuki,[8] T. Takahashi,[30] F. Takasaki,[8] K. Tamai,[8] N. Tamura,[29] M. Tanaka,[8] G. N. Taylor,[21] Y. Teramoto,[30] T. Tomura,[45] K. Trabelsi,[7] T. Tsuboyama,[8] T. Tsukamoto,[8] S. Uehara,[8] K. Ueno,[26] Y. Unno,[2] S. Uno,[8] S. E. Vahsen,[34] G. Varner,[7] K. E. Varvell,[40] C. H. Wang,[25] J. G. Wang,[52] M. Watanabe,[29] Y. Watanabe,[46] E. Won,[15] B. D. Yabsley,[52] Y. Yamada,[8] A. Yamaguchi,[44] H. Yamamoto,[44] Y. Yamashita,[28] M. Yamauchi,[8] Heyoung Yang,[38] Y. Yuan,[10] Y. Yusa,[44] C. C. Zhang,[10] J. Zhang,[50] Z. P. Zhang,[37] Y. Zheng,[7] V. Zhilich,[1] D. Žontar,[19,13] and D. Zürcher[18]

(Belle Collaboration)

[1]*Budker Institute of Nuclear Physics, Novosibirsk*
[2]*Chiba University, Chiba*
[3]*Chuo University, Tokyo*
[4]*University of Cincinnati, Cincinnati, Ohio 45221*
[5]*University of Frankfurt, Frankfurt*
[6]*Gyeongsang National University, Chinju*
[7]*University of Hawaii, Honolulu, Hawaii 96822*
[8]*High Energy Accelerator Research Organization (KEK), Tsukuba*
[9]*Hiroshima Institute of Technology, Hiroshima*
[10]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing*
[11]*Institute of High Energy Physics, Vienna*
[12]*Institute for Theoretical and Experimental Physics, Moscow*
[13]*J. Stefan Institute, Ljubljana*
[14]*Kanagawa University, Yokohama*
[15]*Korea University, Seoul*
[16]*Kyoto University, Kyoto*
[17]*Kyungpook National University, Taegu*
[18]*Institut de Physique des Hautes Énergies, Université de Lausanne, Lausanne*
[19]*University of Ljubljana, Ljubljana*
[20]*University of Maribor, Maribor*
[21]*University of Melbourne, Victoria*
[22]*Nagoya University, Nagoya*
[23]*Nara Women's University, Nara*
[24]*National Kaohsiung Normal University, Kaohsiung*
[25]*National Lien-Ho Institute of Technology, Miao Li*
[26]*National Taiwan University, Taipei*
[27]*H. Niewodniczanski Institute of Nuclear Physics, Krakow*
[28]*Nihon Dental College, Niigata*
[29]*Niigata University, Niigata*
[30]*Osaka City University, Osaka*
[31]*Osaka University, Osaka*
[32]*Panjab University, Chandigarh*
[33]*Peking University, Beijing*

[34]*Princeton University, Princeton, New Jersey 08545*
[35]*RIKEN BNL Research Center, Upton, New York 11973*
[36]*Saga University, Saga*
[37]*University of Science and Technology of China, Hefei*
[38]*Seoul National University, Seoul*
[39]*Sungkyunkwan University, Suwon*
[40]*University of Sydney, Sydney, New South Wales*
[41]*Tata Institute of Fundamental Research, Bombay*
[42]*Toho University, Funabashi*
[43]*Tohoku Gakuin University, Tagajo*
[44]*Tohoku University, Sendai*
[45]*Department of Physics, University of Tokyo, Tokyo*
[46]*Tokyo Institute of Technology, Tokyo*
[47]*Tokyo Metropolitan University, Tokyo*
[48]*Tokyo University of Agriculture and Technology, Tokyo*
[49]*Toyama National College of Maritime Technology, Toyama*
[50]*University of Tsukuba, Tsukuba*
[51]*Utkal University, Bhubaneswer*
[52]*Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061*
[53]*Yokkaichi University, Yokkaichi*
[54]*Yonsei University, Seoul*
[55]*Aomori University, Aomori*

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We report results on the decay $B^-\to D_{CP}K^-$ and its charge conjugate using a data sample of 85.4×10^6 $B\bar{B}$ pairs recorded at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric e^+e^- storage ring. Ratios of branching fractions of Cabibbo-suppressed to Cabibbo-favored processes are determined to be $\mathcal{B}(B^-\to D^0K^-)/\mathcal{B}(B^-\to D^0\pi^-)=0.077\pm0.005(\mathrm{stat})\pm0.006(\mathrm{syst})$, $\mathcal{B}(B^-\to D_1K^-)/\mathcal{B}(B^-\to D_1\pi^-)=0.093\pm0.018(\mathrm{stat})\pm0.008(\mathrm{syst})$ and $\mathcal{B}(B^-\to D_2K^-)/\mathcal{B}(B^-\to D_2\pi^-)=0.108\pm0.019(\mathrm{stat})\pm0.007(\mathrm{syst})$ where the indices 1 and 2 represent the $CP=+1$ and $CP=-1$ eigenstates of the D^0-$\bar{D}^0$ system, respectively. We find the partial-rate charge asymmetries for $B^-\to D_{CP}K^-$ to be $\mathcal{A}_1=0.06\pm0.19(\mathrm{stat})\pm0.04(\mathrm{syst})$ and $\mathcal{A}_2=-0.19\pm0.17(\mathrm{stat})\pm0.05(\mathrm{syst})$.

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The extraction of ϕ_3 [1], an angle of the Kobayashi-Maskawa triangle [2], is a challenging measurement even with modern high luminosity B factories. Recent theoretical work on B meson dynamics has demonstrated the direct accessibility of ϕ_3 using the process $B^-\to DK^-$ [3,4]. If the D^0 is reconstructed as a CP eigenstate, the $b\to c$ and $b\to u$ processes interfere. This interference leads to direct CP violation as well as a characteristic pattern of branching fractions. However, the branching fractions for D meson decay modes to CP eigenstates are only of order 1%. Since CP violation through interference is expected to be small, a large number of B decays is needed to extract ϕ_3. Assuming the absence of D^0-$\bar{D}^0$ mixing, the observables sensitive to CP violation that are used to extract the angle ϕ_3 [5] are

$$\mathcal{A}_{1,2}\equiv\frac{\mathcal{B}(B^-\to D_{1,2}K^-)-\mathcal{B}(B^+\to D_{1,2}K^+)}{\mathcal{B}(B^-\to D_{1,2}K^-)+\mathcal{B}(B^+\to D_{1,2}K^+)}$$

$$=\frac{2r\sin\delta'\sin\phi_3}{1+r^2+2r\cos\delta'\cos\phi_3}$$

$$\mathcal{R}_{1,2}\equiv\frac{R^{D_{1,2}}}{R^{D^0}}=1+r^2+2r\cos\delta'\cos\phi_3,$$

$$\delta'=\begin{cases}\delta & \text{for } D_1\\ \delta+\pi & \text{for } D_2,\end{cases}$$

where the ratios $R^{D_{1,2}}$ and R^{D^0} are defined as

$$R^{D_{1,2}}=\frac{\mathcal{B}(B^-\to D_{1,2}K^-)+\mathcal{B}(B^+\to D_{1,2}K^+)}{\mathcal{B}(B^-\to D_{1,2}\pi^-)+\mathcal{B}(B^+\to D_{1,2}\pi^+)},$$

$$R^{D^0}=\frac{\mathcal{B}(B^-\to D^0K^-)+\mathcal{B}(B^+\to \bar{D}^0K^+)}{\mathcal{B}(B^-\to D^0\pi^-)+\mathcal{B}(B^+\to \bar{D}^0\pi^+)},$$

D_1 and D_2 are CP-even and CP-odd eigenstates of the neutral D meson, $r=|A(B^-\to\bar{D}^0K^-)/A(B^-\to D^0K^-)|$ is the ratio of the amplitudes of the two tree diagrams shown in Fig. 1 and δ is their strong-phase difference. The ratio r corresponds to the magnitude of CP asymmetry and is suppressed to the level of ~0.1 due to the Cabibbo-Kobayashi-

*On leave from Nova Gorica Polytechnic, Nova Gorica.

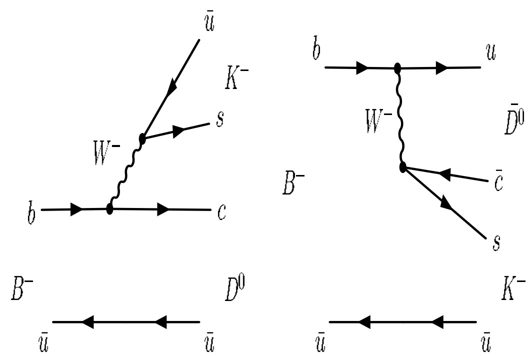

FIG. 1. $B^- \to D^0 K^-$ and $B^- \to \overline{D}{}^0 K^-$.

Maskawa (CKM) factor (~ 0.4) and a color suppression factor (~ 0.25). Note that the asymmetries $\mathcal{A}_1$ and $\mathcal{A}_2$ have opposite signs.

The ratio of the Cabibbo-suppressed decay $B^- \to D^0 K^-$ to the Cabibbo-favored decay $B^- \to D^0 \pi^-$ has been reported by CLEO [6] to be $R^{D^0} = 0.099^{+0.014}_{-0.012}{}^{+0.007}_{-0.006}$ while Belle finds $R^{D^0} = 0.079 \pm 0.009 \pm 0.006$ [7]. Assuming factorization, the ratio R^{D^0} is expected to be $\tan^2\theta_C (f_K/f_\pi)^2 \approx 0.074$ in the tree-level approximation, where θ_C is the Cabibbo angle, and f_K and f_π are meson decay constants. The measurements are in good agreement with this theoretical expectation.

Previously, Belle reported the observation of the decays $B^- \to D_1 K^-$ and $B^- \to D_2 K^-$ with 29.1 fb^{-1} [8]. This paper reports more precise measurements of these decays with a data sample of 78 fb^{-1}, containing 85.4×10^6 $B\overline{B}$ pairs, collected with the Belle detector at the KEKB asymmetric-energy e^+e^- (3.5 on 8 GeV) collider operating at the $\Upsilon(4S)$ resonance. At KEKB, the $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta\gamma = 0.425$ nearly along the electron beam line.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a three-layer silicon vertex detector, a 50-layer central drift chamber (CDC), an array of silica aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight (TOF) scintillation counters, and an electromagnetic calorimeter comprised of CsI(Tl) crystals located inside a super-conducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [9].

We reconstruct D^0 mesons in the following decay channels. For the flavor specific mode (denoted by D_f), we use $D^0 \to K^-\pi^+$ [10]. For $CP = +1$ modes, we use $D_1 \to K^-K^+$ and $\pi^-\pi^+$ while for $CP = -1$ modes, we use $D_2 \to K_S^0\pi^0$, $K_S^0\phi$, $K_S^0\omega$, $K_S^0\eta$ and $K_S^0\eta'$.

The charged track, K_S^0 and π^0 selection requirements have been described in Ref. [8]. For each charged track, information from the ACC, TOF and specific ionization measurements from the CDC are used to determine a K/π likelihood ratio $P(K/\pi) = L_K/(L_K + L_\pi)$, where L_K and L_π are kaon and pion likelihoods. The particle identification requirements and cuts on other kinematic variables are optimized using continuum background and signal Monte Carlo. For kaons (pions) from the $D^0 \to K^-\pi^+$ mode we used the particle identification requirement of $P(K/\pi) > 0.4$ (< 0.7). For kaons from the $D^0 \to K^-K^+$ mode we require $P(K/\pi) > 0.7$ while for pions from $D^0 \to \pi^-\pi^+$ mode we require $P(K/\pi) < 0.7$.

The ω mesons are reconstructed from $\pi^+\pi^-\pi^0$ combinations in the mass window 0.732 GeV/$c^2 < M(\pi^+\pi^-\pi^0) < 0.82$ GeV/c^2 with the charged pion particle identification requirement $P(K/\pi) < 0.8$. To reduce the contribution from the non-resonant background, a helicity angle cut $|\cos\theta_{\mathrm{hel}}| > 0.4$ is applied where θ_{hel} is the angle between the normal to the ω decay plane in the ω rest frame and the ω momentum in the D^0 rest frame. To remove the contribution from $D^0 \to K^{*-}\rho^+$, we require the $K_S^0\pi^-$ invariant mass to be greater than 75 MeV/c^2 from the K^{*-} nominal mass.

The ϕ mesons are reconstructed from two oppositely charged kaons in the mass window of 1.008 GeV/$c^2 < M(K^+K^-) < 1.032$ GeV/c^2 with $P(K/\pi) > 0.2$. We also apply the ϕ helicity angle cut $|\cos\theta_{\mathrm{hel}}| > 0.4$ where θ_{hel} is the angle between one of the ϕ daughters in the ϕ rest frame and the ϕ momentum in the D^0 rest frame. We form candidate η and η' mesons using the $\gamma\gamma$ and $\eta\pi^+\pi^-$ decay modes with mass ranges of 0.495 GeV/$c^2 < M(\gamma\gamma) < 0.578$ GeV/c^2 and 0.903 GeV/$c^2 < M(\eta\pi^+\pi^-) < 1.002$ GeV/c^2, respectively. The η momentum is required to be greater than 0.5 GeV/c. Both η and η' candidates are kinematically constrained to their nominal masses. The D^0 candidates are required to have masses within $\pm 2.5\sigma$ of their nominal masses, where σ is the measured mass resolution which ranges from 4.9 MeV to 17.7 MeV depending on the decay channel. A D^0 mass and (wherever possible) vertex constrained fit is then performed on the remaining candidates.

We combine the D^0 and π^-/K^- candidates (denoted by h) to form B candidates. We apply tighter particle identification cuts, $P(K/\pi) > 0.8$ (< 0.8) for prompt kaons (pions), to identify $B^- \to D^0 K^- (\pi^-)$ events. The signal is identified by two kinematic variables calculated in the center-of-mass (c.m.) frame. The first is the beam-energy constrained mass, $M_{\mathrm{bc}} = \sqrt{E_{\mathrm{beam}}^2 - |\vec{p}_D + \vec{p}_h|^2}$, where $\vec{p}_D$ and $\vec{p}_h$ are the momenta of D^0 and K^-/π^- candidates and E_{beam} is the beam energy in the c.m. frame. The second is the energy difference, $\Delta E = E_D + E_h - E_{\mathrm{beam}}$, where E_D is the energy of the D^0 candidate, E_h is the energy of the K^-/π^- candidate calculated from the measured momentum and assuming the pion mass, $E_h = \sqrt{|\vec{p}_h|^2 + m_\pi^2}$. With this definition, real $B^- \to D^0\pi^-$ events peak at $\Delta E = 0$ even when they are misidentified as $B^- \to D^0 K^-$, while $B^- \to D^0 K^-$ events peak around $\Delta E = -49$ MeV. Event candidates are accepted if they have 5.2 GeV/$c^2 < M_{\mathrm{bc}} < 5.3$ GeV/c^2 and $|\Delta E| < 0.2$ GeV. In case of multiple candidates from a single event, we choose the best candidate on the basis of a χ^2 determined from the differences between the measured and nominal values of M_D and M_{bc}. The fraction of multiple candidates is less than 2%. According to Monte Carlo simulation the correct candidate is chosen in all cases.

To suppress the large combinatorial background from the two-jet continuum processes such as $e^+e^- \to q\overline{q}$ ($q = u$, d, s or c), variables that characterize the event topology are used.

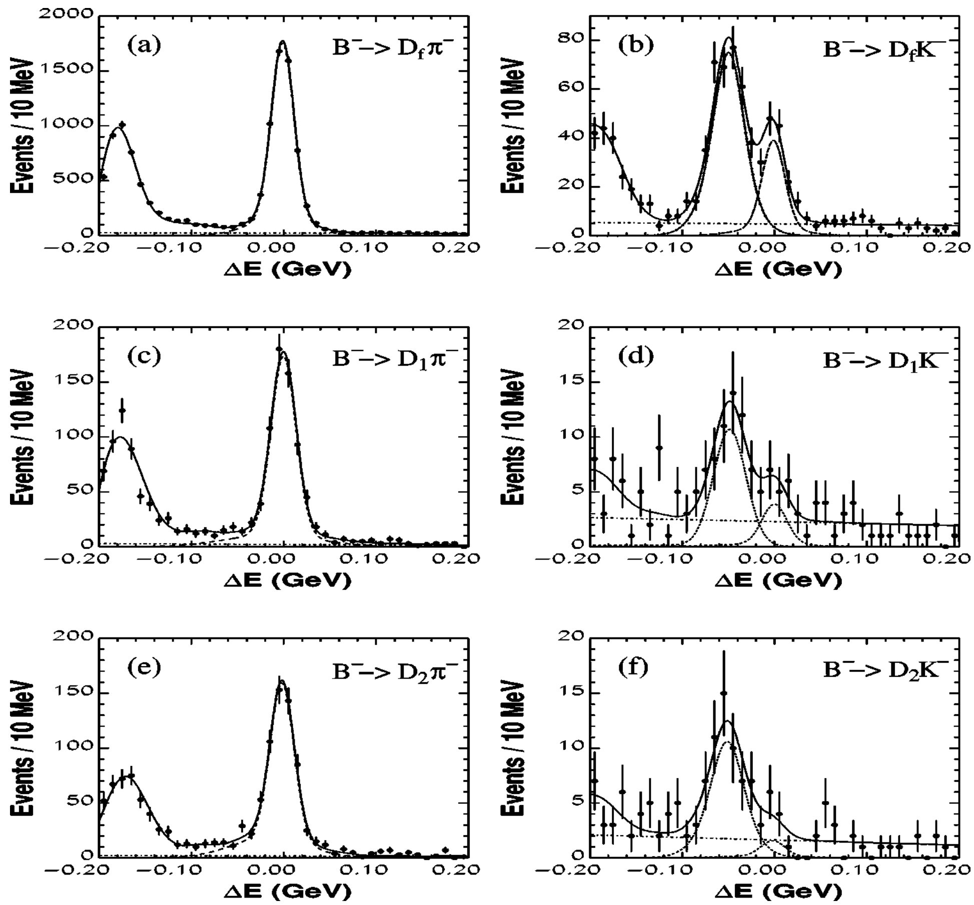

FIG. 2. ΔE distributions for (a) $B^- \to D_f \pi^-$, (b) $B^- \to D_f K^-$, (c) $B^- \to D_1 \pi^-$, (d) $B^- \to D_1 K^-$, (e) $B^- \to D_2 \pi^-$ and (f) $B^- \to D_2 K^-$. Points with error bars are the data and the solid lines show the fit results.

We construct a Fisher discriminant F, from 6 modified Fox-Wolfram moments [11]. Furthermore, $\cos\theta_B$, the angle of the B flight direction with respect to the beam axis is also used to distinguish signal from continuum background. We combine these two independent variables F and $\cos\theta_B$ to make a single likelihood ratio (LR) variable that distinguishes signal from continuum background. We apply a different requirement for each sub-mode based on the expected signal yield and the backgrounds in the $M_{\rm bc}$ sideband data. For $B^- \to D^0 \pi^-$ where $D^0 \to K^- \pi^+$, $K^- K^+$ we require $LR > 0.4$, whereas for $D^0 \to \pi^+ \pi^-$, $K_S^0 \pi^0$, $K_S^0 \phi$, $K_S^0 \omega$, $K_S^0 \eta$ and $K_S^0 \eta'$ we require $LR > 0.6$. To give an example of the performance of this selection, the $LR > 0.4$ requirement keeps 87.5% of the $B^- \to D^0[\to K^- \pi^+]\pi^-$ signal while removing 73% of the continuum background.

The signal yields are extracted from a fit to the ΔE distribution in the region $5.27\ \mathrm{GeV}/c^2 < M_{\rm bc} < 5.29\ \mathrm{GeV}/c^2$. The $B^- \to D^0 \pi^-$ signal is parametrized as a double Gaussian with peak position and width floated. On the other hand, we calibrate the shape parameters of the $B^- \to D^0 K^-$ signal using the $B^- \to D^0 \pi^-$ data. This accounts for the kinematical shifts and smearing of the ΔE peaks caused by the incorrect mass assignments of prompt hadrons. The peak position and width of the $B^- \to D^0 K^-$ signal events are determined by fitting the $B^- \to D^0 \pi^-$ distribution using the kaon mass hypothesis for the prompt pion, where the relative peak position is reversed with respect to the origin. The shape parameters for the feed across from $B^- \to D^0 \pi^-$ are fixed by the fit results of the $B^- \to D^0 \pi^-$ enriched sample. The continuum background is modeled as a first order polynomial function with parameters determined from the ΔE distribution for the events in the sideband region $5.2\ \mathrm{GeV}/c^2 < M_{\rm bc} < 5.26\ \mathrm{GeV}/c^2$. Backgrounds from other B decays including contributions from $B^- \to D^{*0} K^-$ and $B^- \to D^0 K^{*-}$ are modeled as a smoothed histogram from Monte Carlo simulation. The fit results are shown in Fig. 2.

The ratios of branching fractions of Cabibbo-suppressed to Cabibbo-favored processes are determined as follows [12]:

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

where N is the number of observed events, η and ϵ are the signal detection and the prompt pion/kaon identification efficiencies, respectively. The signal detection efficiencies were determined from a Monte Carlo simulation e.g. $\eta(B^- \to D_f \pi^-) = (44.6 \pm 0.7)\%$ and $\eta(B^- \to D_f K^-) = (42.5 \pm 0.7)\%$. The particle identification efficiencies for the prompt pion and kaon, $\epsilon(\pi)$ and $\epsilon(K)$, are determined

TABLE I. Signal yields, feed-acrosses and ratios of branching fractions. The errors on R^D are statistical and systematic, respectively.

Mode	$B^-\to D\pi^-$ events	$B^-\to DK^-$ events	$B\to D\pi^-$ feed-across	$R^D=\frac{\mathcal{B}(B^-\to D^0K^-)}{\mathcal{B}(B^-\to D^0\pi^-)}$
$B^-\to D_f h^-$	6052 ± 88	347.5 ± 21	134.4 ± 14.7	$0.077\pm 0.005\pm 0.006$
$B^-\to D_1 h^-$	683.4 ± 32.8	47.3 ± 8.9	15.6 ± 6.4	$0.093\pm 0.018\pm 0.008$
$B^-\to D_2 h^-$	648.3 ± 31.0	52.4 ± 9.0	6.3 ± 5.0	$0.108\pm 0.019\pm 0.007$

from a kinematically selected sample of $D^{*+}\to D^0[\to K^-\pi^+]\pi^+$ decays, where the K^- and π^+ mesons from D^0 candidates have been selected in the same c.m. momentum (2.1 GeV/$c<p_{\rm c.m.}<2.5$ GeV/c) and polar angle regions as prompt hadrons in the $B^-\to Dh^-$ decay. With our requirement $P(K/\pi)>0.8$, the efficiencies were determined to be $\epsilon(K)=0.768\pm 0.001$ and $\epsilon(\pi)=0.976\pm 0.001$, and the rate for misidentification of π as K is 0.024 ± 0.001. The ratio of $B\to D\pi^-$ feed-across in the $B\to DK^-$ signal to $B\to D\pi^-$ signal is 2%–2.5%, which is consistent with the measured pion fake rate. The ratios of Cabibbo-suppressed to Cabibbo-favored decay modes are shown in Table I. The double ratios are found to be

$$\mathcal{R}_1=1.21\pm 0.25(\text{stat})\pm 0.14(\text{syst}),$$

$$\mathcal{R}_2=1.41\pm 0.27(\text{stat})\pm 0.15(\text{syst})$$

for CP-even and CP-odd eigenstates, respectively. The systematic errors in the ratios R^D are due to the uncertainty in yield extraction (3%–7%) and particle identification (1%). The systematic error in the yield extraction includes uncertainties in the $B\bar{B}$ background and signal shape parametrization. The uncertainty in the ΔE signal shape parametrization was determined by varying the mean and width of the double Gaussian parameters within their errors. The uncertainty from the slope of the background was determined by changing its value by its error. Both of the resulting changes were included in the systematic error from fitting. Also other backgrounds including rare decays such as $B^-\to K^-K^+K^-$ and $B^-\to K^-\pi^+\pi^-$, which could contribute to the ΔE signal region, are estimated from the D^0 sideband data. This uncertainty (0.5%–3%) is also included as a source of systematic error.

The asymmetries $\mathcal{A}_{1,2}$ are evaluated using signal yields obtained from separate fits to the B^+ and B^- samples shown in Fig. 3. The results are given in Table II. We find

$$\mathcal{A}_1=0.06\pm 0.19(\text{stat})\pm 0.04(\text{syst}),$$

$$\mathcal{A}_2=-0.19\pm 0.17(\text{stat})\pm 0.05(\text{syst}),$$

where the systematic uncertainty is from the intrinsic detector charge asymmetry (3.2%), the B^- and B^+ yield extractions (2.4%–3.3%), and the asymmetry in particle identification efficiency of prompt kaons (1%). The intrinsic detector charge asymmetry is calculated from the $B^-\to D^0[\to K^-\pi^+]\pi^-$ sample. The systematic error from yield extraction is calculated by changing the fitting parameters by $\pm 1\sigma$.

In summary, using 78 fb^{-1} of data collected with the Belle detector, we report measurements of the decays B^-

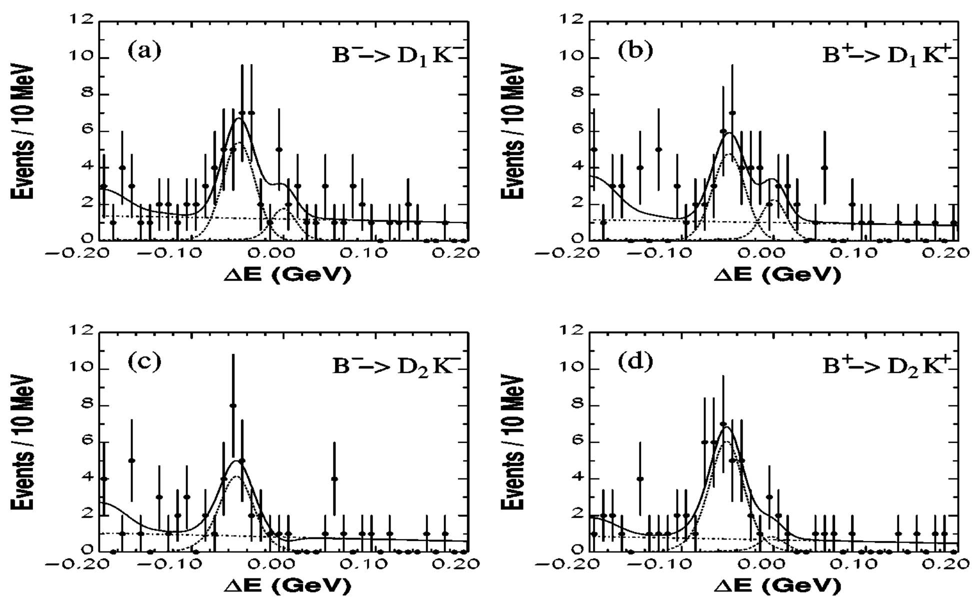

FIG. 3. ΔE distributions for the charge conjugate modes (a) $B^-\to D_1K^-$, (b) $B^+\to D_1K^+$, (c) $B^-\to D_2K^-$, (d) $B^+\to D_2K^+$.

TABLE II. Yields, partial-rate charge asymmetries and 90% C.L. intervals for asymmetries.

Mode	$N(B^+)$	$N(B^-)$	$\mathcal{A}_{CP}$	90% C.L.
$B^\pm \to D_f K^\pm$	165.4 ± 14.5	179.6 ± 15	$0.04 \pm 0.06 \pm 0.03$	$-0.07 < \mathcal{A}_f < 0.15$
$B^\pm \to D_1 K^\pm$	22.1 ± 6.1	25.0 ± 6.5	$0.06 \pm 0.19 \pm 0.04$	$-0.26 < \mathcal{A}_1 < 0.38$
$B^\pm \to D_2 K^\pm$	29.9 ± 6.5	20.5 ± 5.6	$-0.19 \pm 0.17 \pm 0.05$	$-0.47 < \mathcal{A}_2 < 0.11$

$\to D_{CP} K^-$, where D_{CP} are the neutral D meson CP eigenstates. These supersede the results reported in [7,8]. The ratios of the branching fractions $R^{D_{1,2}}$ for the decays $B^- \to D_{CP} K^-$ and $B^- \to D_{CP} \pi^-$ are consistent with those for the flavor specific decay within errors. The measured partial-rate charge asymmetries $\mathcal{A}_{1,2}$ are consistent with zero.

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[1] Another naming convention, γ $(=\phi_3)$, is also used in the literature.

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