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Study of $B^{\pm} \to D_{CP}K^{\pm}$ and $D^{*}_{CP}K^{\pm}$ decays

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We report a study of the modes $B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D^{*}K^{\pm}$ where $D^{(*)}$ decays to CP eigenstates. The data sample used contains 275×10^6 $B\bar{B}$ events at the $\Upsilon(4S)$ resonance collected by the Belle detector at the KEKB energy-asymmetric e^+e^- collider. The CP asymmetries obtained for $D_{CP}K$ are: $\mathcal{A}_1 = 0.06 \pm 0.14(\text{stat}) \pm 0.05(\text{sys})$, $\mathcal{A}_2 = -0.12 \pm 0.14(\text{stat}) \pm 0.05(\text{sys})$ and for $D^*_{CP}K$: $\mathcal{A}^*_1 = -0.20 \pm 0.22(\text{stat}) \pm 0.04(\text{sys})$, $\mathcal{A}^*_2 = 0.13 \pm 0.30(\text{stat}) \pm 0.08(\text{sys})$.

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Measurements of the decay rates of $B^{\pm} \to D^{(*)}K^{\pm}$ provide a theoretically clean method for extracting the unitarity triangle angle ϕ_3, an angle in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [1]. Since both a D^0 and a $\bar{D}^0$ can decay into the same CP eigenstate (D_{CP}, or D_1 for a CP-even state and D_2 for a CP-odd state), the $b \to c$ and $b \to u$ processes shown in Fig. 1 interfere in the $B^{\pm} \to D_{CP}K^{\pm}$ decay channel. This interference may lead to direct CP violation. To measure D meson decays to CP eigenstates, a large number of B meson decays is required since the branching fractions to these modes are of order 1%. To extract ϕ_3 using the GLW method [2], the following observables sensitive to CP violation must be measured: the asymmetries

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

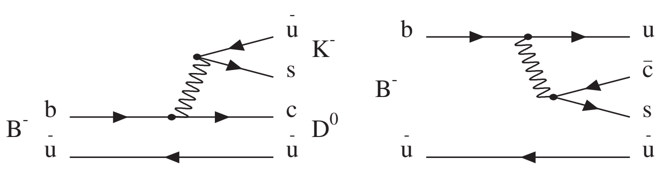

FIG. 1. Feynman diagrams for $B^- \to D^0K^-$ and $B^- \to \bar{D}^0K^-$.

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

and the double ratios

$$\mathcal{R}_{1,2} \equiv \frac{R^{D_{1,2}}}{R^{D^0}} = 1 + r^2 + 2r\cos\delta'\cos\phi_3 \quad (3)$$

$$\delta' = \begin{cases} \delta & \text{for } D_1 \\ \delta + \pi & \text{for } D_2. \end{cases} \quad (4)$$

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

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

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

where $r \equiv |A(B^- \to \bar{D}^0K^-)/A(B^- \to D^0K^-)|$ is the ratio of the magnitudes of the two tree diagrams shown in Fig. 1, δ is their strong-phase difference. The ratio r is given by the product of CKM factors and a color suppression factor that characterizes the magnitude of CP asymmetry. The asymmetries and double ratios can be calculated for D^* in a similar manner (notation $\mathcal{A}^*_{1,2}$ and $\mathcal{R}^*_{1,2}$). Here we have assumed that mixing and CP violation in the neutral D meson system can be neglected.

Previously, Belle [3] and *BABAR* [4] reported the observation of the decays $B^- \to D_1K^-$ and $B^- \to D_2K^-$. *BABAR* [5] also reported the observation of the decay $B^- \to D_1^*K^-$. This paper reports more precise measurements of the $B^- \to D_{CP}K^-$ channels, superseding our previous result, and a study of the decays $B^- \to D_1^*K^-$ and $B^- \to D_2^*K^-$ with a data sample corresponding to 275×10^6 $B\bar{B}$ pairs.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting 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 [6].

D^0 mesons are reconstructed in the Cabibbo-favored modes (D_f) [7]: $K^-\pi^+$, CP-even modes (D_1): K^+K^-, $\pi^-\pi^+$, and CP-odd modes (D_2): $K_S^0\pi^0$, $K_S^0\omega$, $K_S^0\phi$.

Neutral pions are reconstructed from pairs of photons, selected in the invariant mass range $118\ \text{MeV}/c^2 < M(\gamma\gamma) < 150\ \text{MeV}/c^2$, corresponding to a $\pm 2.5\sigma$ window, where σ is the π^0 mass resolution. Each photon is required to have energy greater than 30 MeV in the laboratory frame, and also in this frame the pion candidate's momentum must exceed (0.1) GeV/c for the $K_S^0\pi^0$ ($K_S^0\omega$) mode. The π^0 candidates are kinematically constrained to the nominal π^0 mass.

Each charged track not coming from a K_S^0 candidate is required to be consistent with coming from the interaction point (IP). For each charged track, information from the ACC, TOF, and CDC is used to identify the particle (PID) as either a pion or kaon via the K/π likelihood ratio $P(K/\pi) = L_K/(L_K + L_\pi)$, where L_K and L_π are kaon and pion likelihoods. With the exception of the prompt kaon from the B meson decay ("fast track"), all kaon candidates must satisfy the PID requirement, $P(K/\pi) > 0.3$. This requirement selects kaons with an efficiency of 92% and a pion misidentification rate of 18%.

The K_S^0 candidates are formed from two oppositely charged pions with an invariant mass required to be within $8.5\ \text{MeV}/c^2$ of the nominal mass ($\sim 3\sigma$). The ϕ meson is reconstructed from two oppositely charged kaons in a mass window $|M(K^+K^-) - m_\phi| < 10\ \text{MeV}/c^2$. ω mesons are reconstructed from $\pi^+\pi^-\pi^0$ combinations in the mass window $0.757\ \text{GeV}/c^2 < M(\pi^+\pi^-\pi^0) < 0.82\ \text{GeV}/c^2$; a loose requirement of $P(K/\pi) < 0.9$ is applied to the charged pions in the ω candidate.

For the D candidates, a 3σ mass requirement is applied, where σ is the D mass resolution which ranges from 5 to 12 MeV. D^* candidates are reconstructed in the $D\pi^0$ decay channel depending on the decay channel. The mass difference between D^* and D candidates is required to be within $2.8\ \text{MeV}/c^2$ ($\sim 3\sigma$) of the nominal value [8]. B meson candidates are formed by combining the $D^{(*)}$ candidates with one charged track (denoted $h^\pm$). The signal is identified by two kinematic variables: the beam-constrained mass M_{bc} and the energy difference ΔE calculated in the $\Upsilon(4S)$ center of mass (CM) frame, $M_{\text{bc}} \equiv \sqrt{E_{\text{beam}}^2 - |\vec{p}_D + \vec{p}_h|^2}$ and $\Delta E \equiv E_D + E_h - E_{\text{beam}}$, where E_{beam} is the beam energy, $\vec{p}_D$ and E_D are the momentum and energy of the D^0 candidate, and $\vec{p}_h$ and E_h are the momentum and energy of the K^-/π^- candidate assuming the pion mass. With this definition, $B^- \to D^0\pi^-$ events peak at $\Delta E = 0$, while $B^- \to D^0K^-$ events peak around $\Delta E = -49$ MeV. Signal candidates are selected with $M_{\text{bc}} > 5.2\ \text{GeV}/c^2$ and $|\Delta E| < 0.2$ GeV. The experimental resolution for M_{bc} is approximately 3 MeV, dominated by the beam energy spread. The ΔE resolution is typically 10 MeV for all-charged-particle final states (D_1 modes). For final states with photons or neutral pions, the ΔE resolution becomes broader and somewhat skewed to negative values.

Event topology is used to distinguish $B\bar{B}$ events from the continuum background. At the $\Upsilon(4S)$, the two B mesons are produced nearly at rest so these events tend to be spherical, whereas continuum events have a two-jet topology. We construct a Fisher discriminant [9] of modified Fox-Wolfram moments called the Super-Fox-Wolfram (SFW) [10], where the Fisher coefficients are optimized by maximizing the separation between $B\bar{B}$ events and continuum events. The angle in the CM frame between the B flight direction and the beam axis, $\cos\theta_B$, is also used. These two independent variables (SFW and $\cos\theta_B$) are combined to form a likelihood ratio: $\mathcal{R} = L_{\text{sig}}/(L_{\text{sig}} + L_{\text{cont}})$, where L_{sig} and L_{cont} are defined as the product of SFW and $\cos\theta_B$ likelihood. The $\mathcal{R}$ requirement is optimized for each submode of DK and D^*K using $N_S/\sqrt{N_S + N_B}$, where $N_S(N_B)$ is the expected number of signal (background) events in the signal region (the coefficients used for the Fisher discriminant are common to all the submodes). The expected number of signal events is obtained assuming the branching ratio given in the Review of Particle Physics [8]. Since the continuum background is negligible for the $K_S^0\phi$ mode, we do not apply an $\mathcal{R}$ requirement.

For events with more than one candidate (1%–2% for all modes, except for $K_S^0\omega$, ~10%), a single candidate is selected on the basis of a χ^2 determined from the difference between the measured and nominal values of masses (D, D^*, K_S^0, ω, ϕ masses) and then the highest $\mathcal{R}$ value.

Signal yields are obtained from fitting the ΔE distributions for $5.27\ \text{GeV}/c^2 < M_{\text{bc}} < 5.29\ \text{GeV}/c^2$. The PID for the fast π or K is used to distinguish between $D^{(*)}\pi$

and $D^{(*)}K$ modes [with a requirement $P(K/\pi) > 0.8$ for $D^{(*)}K$, which selects kaons with an efficiency of 80% and a pion misidentification rate of 7%, and the remainder as $D^{(*)}\pi$]. Signal peaks are fitted with double Gaussians. Shifts in the mean position and differences in resolution seen between Monte Carlo (MC) and data in $D\pi$ are used to correct the DK fits in data. The continuum background is modeled by a first order polynomial whose slope is obtained from the M_{bc} sideband ($M_{bc} < 5.25$ GeV/c^2). Backgrounds from B meson decays are modeled by large MC samples using a smoothed histogram. When statistics are small, as is the case in D^*K, shapes from $D^*\pi$ are used directly.

Backgrounds are studied using MC samples for known backgrounds and D^0 sidebands in data. A peaking background is found for $B \to DK$ (where $D \to \pi\pi$) coming from $B \to D\pi$ ($D \to K\pi$), which is suppressed by making a 3σ mass requirement on the $K\pi$ invariant mass.

For DK, in the K^+K^- and $\pi^+\pi^-$ modes, clear peaks are seen in the D mass sideband, defined as $1.80\ \text{GeV}/c^2 < M(hh) < 1.83\ \text{GeV}/c^2$ and $1.90\ \text{GeV}/c^2 < M(hh) < 1.93\ \text{GeV}/c^2$, where h is a charged kaon or pion. These peaks come from the $B \to KKK$ and $B \to K\pi\pi$ modes, respectively. The yields obtained (63.5 ± 7.5 events) are in agreement with the results of a dedicated study of these channels [11] and allow an estimate of the peaking backgrounds for these modes. The sidebands are scaled (factor 0.5) and subtracted from the yields of D_1, and hence are taken into account in the asymmetries and double ratios defined in Eqs. (1)–(3). Note that such effects are not seen in $B \to D^*K$ since the D^* provides an extra constraint to reduce these backgrounds.

Backgrounds in the D_2 modes, $K_S^0\omega$ and $K_S^0\phi$, need careful consideration because they can be modes of non-CP or with opposite CP (opposite asymmetry) to the mode considered. Possible backgrounds to $K_S^0\omega$ include non-CP modes $K_S^0\pi\pi\pi^0$ and $K^*\rho$, and backgrounds to $K_S^0\phi$ include non-CP modes $a_0^{\pm}(980)K^{\mp}$, K_S^0KK, and opposite CP modes $K_S^0a_0^0(980)$ and $K_S^0f_0(980)$. To determine contributions from these backgrounds, the data ΔE distributions for $D\pi$ modes are fitted in bins of ω or ϕ helicity angle. The helicity angle θ_{hel} for ϕ (ω) is defined as the angle between one of the kaons from ϕ (the normal to the ω decay plane) and D momentum in the ϕ (ω) rest frame. The yields as a function of helicity angle are then fitted allowing for possible contributions from signal and either $K_S^0\pi\pi\pi^0$ and K_S^0KK. The fraction of signal is estimated to be $88.8 \pm 8.4\%$ for $K_S^0\omega$ and $84.0 \pm 12.5\%$ for $K_S^0\phi$. When a helicity requirement ($|\cos\theta_{hel}| > 0.4$) is imposed to further reduce the backgrounds, these fractions become $92.4 \pm 9.8\%$ for $K_S^0\omega$ and $88.6 \pm 11.1\%$ for $K_S^0\phi$.

The fitted ΔE distributions for positively and negatively charged B meson candidates are shown in Fig. 2. Table I gives the corresponding yields and asymmetries with their statistical uncertainties. The asymmetries in the control samples (D_f) are consistent with zero, as expected. The modes of interest are D_1K and D_2K: the B^+ and B^- yields are used to calculate asymmetries after peaking background subtraction for D_1. For D_2 modes, the asymmetry is estimated mode by mode and the dilution factor due to the CP content of the background is taken into account, assuming no CP for $K_S^0\omega$ background and opposite CP for $K_S^0\phi$ background.

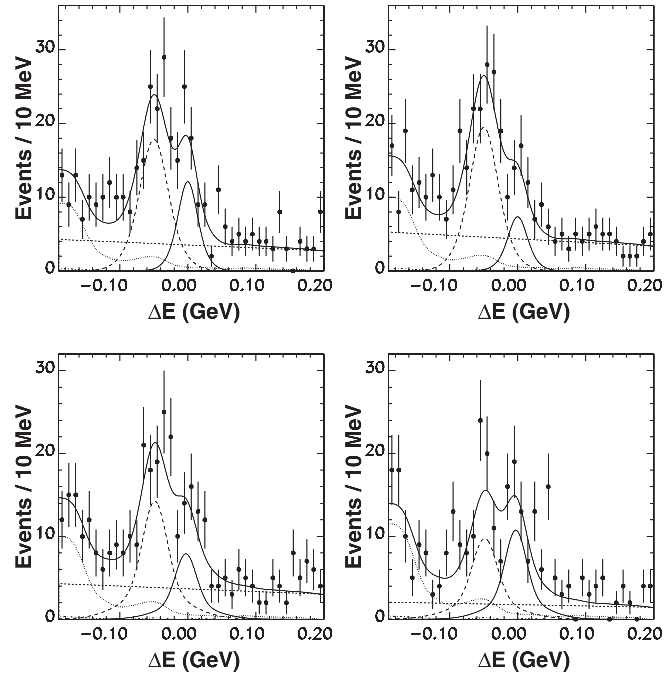

FIG. 2. ΔE distributions for (top left) $B^+ \to D_1K^+$, (top right) $B^- \to D_1K^-$, (bottom left) $B^+ \to D_2K^+$, (bottom right) $B^- \to D_2K^-$. Points with error bars are the data and the solid lines show the fit results. The components of the fit are the background from B meson decays (dotted line), the continuum background (dashed line), the signal DK (left) and $D\pi$ (right).

The yields obtained for D_1^*K and D_2^*K (Fig. 3) are 43.9 ± 10.2 and 32.7 ± 10.0 respectively, which corre-

TABLE I. Yields and asymmetries obtained for Dh and D^*h modes. For D_2 modes, the asymmetry is estimated mode by mode taking into account the CP content of the background.

	$\sum B$	B^+	B^-	$\mathcal{A}$
$D_f\pi$	19266 ± 150	9677 ± 103	9521 ± 102	-0.008 ± 0.008
$D_1\pi$	2163 ± 56	1049 ± 38	1124 ± 37	0.035 ± 0.024
$D_2\pi$	2168 ± 61			0.017 ± 0.026
D_fK	1131 ± 41	528 ± 28	603 ± 29	0.066 ± 0.036
D_1K	143.3 ± 21.9	70.2 ± 14.7	79.2 ± 15.7	$0.060 \pm 0.144 \pm 0.046$
D_2K	149.5 ± 19.0			$-0.117 \pm 0.141 \pm 0.049$
$D^*\pi$	5434 ± 101	2756 ± 59	2678 ± 59	-0.014 ± 0.015
$D_1^*\pi$	662 ± 37	338 ± 21	322 ± 21	-0.021 ± 0.045
$D_2^*\pi$	604 ± 38			-0.090 ± 0.051
D^*K	256 ± 22	140 ± 16	117 ± 15	-0.089 ± 0.086
D_1^*K	43.9 ± 10.2	27.3 ± 7.4	18.2 ± 6.9	$-0.200 \pm 0.224 \pm 0.035$
D_2^*K	32.7 ± 10.0			$0.131 \pm 0.300 \pm 0.076$

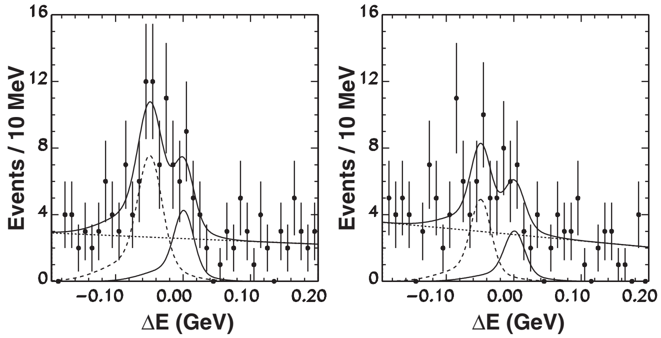

FIG. 3. ΔE distributions for (left) $B^{\pm} \to D_1^{*0}K^{\pm}$ and (right) $B^{\pm} \to D_2^{*0}K^{\pm}$. Points with error bars are the data and the solid lines show the fit results.

spond to significances of 5.2σ and 3.3σ ($K_S^0\pi^0\, 2.9\sigma$, $K_S^0\omega\, 0.9\sigma$, $K_S^0\phi\, 1.4\sigma$) where the significance is calculated as $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\max})}$, where $\mathcal{L}_{\max}$ and $\mathcal{L}_0$ denote the maximum likelihood with the nominal signal yield and with signal yield fixed to 0, respectively.

The sources of systematic errors for the double ratios come from the uncertainty in yield extraction, uncertainty in signal fractions for $K_S^0\omega$ and $K_S^0\phi$ (1%), and the uncertainty in the contributions of peaking background from D sideband data. The uncertainty in yield extraction is estimated by varying the fitting parameters, such as the slope used for continuum or widths and means for Gaussians used for signals by $\pm 1\sigma$ (6%–8%). The uncertainty due to peaking D sidebands is taken from the error on the estimated contribution: 6% for $\mathcal{R}_1$. These errors are added in quadrature for $D_1^{(*)}$ and $D_2^{(*)}$.

Systematic errors for $\mathcal{A}$ are from intrinsic detector charge asymmetry, measured from the control samples $B \to D_f\pi$, (0.02), uncertainty in signal fraction for $K_S^0\omega$ and $K_S^0\phi$ and on the CP content assumption of the peaking background (0.01), yield extraction (0.02–0.04) and PID (0.01).

The asymmetries for $D_{1,2}K$, $\mathcal{A}_1$, and $\mathcal{A}_2$, are found to be

$$\mathcal{A}_1 = 0.06 \pm 0.14(\mathrm{stat}) \pm 0.05(\mathrm{sys})$$
$$\mathcal{A}_2 = -0.12 \pm 0.14(\mathrm{stat}) \pm 0.05(\mathrm{sys}).$$

The double ratios are

$$\mathcal{R}_1 = 1.13 \pm 0.16(\mathrm{stat}) \pm 0.08(\mathrm{sys})$$
$$\mathcal{R}_2 = 1.17 \pm 0.14(\mathrm{stat}) \pm 0.14(\mathrm{sys}).$$

The asymmetries for $D^{*}_{1,2}K$ are found to be

$$\mathcal{A}_1^{*} = -0.20 \pm 0.22(\mathrm{stat}) \pm 0.04(\mathrm{sys})$$
$$\mathcal{A}_2^{*} = 0.13 \pm 0.30(\mathrm{stat}) \pm 0.08(\mathrm{sys}),$$

where the systematic errors are calculated in a similar way to the Dh case. The double ratios found are

$$\mathcal{R}_1^{*} = 1.41 \pm 0.25(\mathrm{stat}) \pm 0.06(\mathrm{sys})$$
$$\mathcal{R}_2^{*} = 1.15 \pm 0.31(\mathrm{stat}) \pm 0.12(\mathrm{sys}).$$

For each state such as $B \to D_{CP}K$ four observables are measured ($\mathcal{A}_1$, $\mathcal{A}_2$, $\mathcal{R}_1$, $\mathcal{R}_2$). Since these are related by $\mathcal{A}_1\mathcal{R}_1 = -\mathcal{A}_2\mathcal{R}_2$ there are then only three independent observables and there are also three physics quantities that should be extracted, ϕ_3, r_{DK}, and δ_{DK}. The measured asymmetries are consistent within errors with zero and also with the standard model expectation. These measurements, while not sufficiently accurate to provide a measurement of ϕ_3, can be used to constrain ϕ_3 through a global fit [12], and the addition of modes such as $D^{*}_{CP}K$ can add further constraints [13].

In summary, using 275×10^6 $B\bar{B}$ events this paper reports results from the decays $B^{\pm} \to D_{CP}K^{\pm}$ and $B^{\pm} \to D^{*}_{CP}K^{\pm}$ where the CP eigenstates are those of the D meson. The partial rate asymmetries $\mathcal{A}_{1,2}$ are measured in both cases and are consistent with zero. The study of $B \to D_{CP}K$ is made with 3 times the statistics of previous studies. $B \to D_1^{*}K$ and $B \to D_2^{*}K$ are observed and their asymmetries and double ratios are also measured.

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