Study of the Suppressed Decays $B^- \rightarrow [K^+ \pi^-]_D K^-$ and $B^- \rightarrow [K^+ \pi^-]_D \pi^-$


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Precise measurements of the elements of the Cabibbo-Kobayashi-Maskawa matrix [1] constrain the standard model and may reveal new physics. However, the extraction of the unitarity triangle angle $\phi_3$ [2] is a challenging measurement even with modern high luminosity $B$ factories. Several methods for measuring $\phi_3$ use the interference between $B^- \rightarrow D^0 K^-$ and $B^+ \rightarrow D^0 K^+$, which occurs when $D^0$ and $\bar{D}^0$ decay to common final states [3,4]. CP violation occurs when both weak and strong phase differences between the amplitudes are nontrivial. As noted by Atwood, Dunietz, and Soni [5], CP violation effects are enhanced if the final state is chosen so that the interfering amplitudes have comparable magnitudes; the archetype uses $B^- \rightarrow [K^+ \pi^-]_D K^-$, where $[K^+ \pi^-]_D$ indicates that the $K^+\pi^-$ pair originates from a neutral $D$ meson. In this case, the color-allowed $B$ decay followed by the doubly Cabibbo-suppressed $D$ decay interferes with the color-suppressed $B$ decay followed by the Cabibbo-allowed $D$ decay (Fig. 1). Previous studies of this decay mode have not found any signals [6]. For the suppressed decay $B^- \rightarrow [K^+ \pi^-]_D \pi^-$, both topology and phenomenology are similar to $B^- \rightarrow [K^+ \pi^-]_D K^-$. In this analysis, the favored decays $B^- \rightarrow [K^- \pi^+]_D h^-$, where $h = \pi$ or $K$, are used as control samples to reduce systematic uncertainties. The same selection criteria for the suppressed decay modes are applied to the control samples whenever possible. Throughout this Letter, charge conjugate reactions are implied except where explicitly mentioned, and we denote the analyzed decay modes as follows:

Suppressed decay $B^- \rightarrow [K^+ \pi^-]_D h^-$, $B^- \rightarrow D_{sup} h^-$.  
Favored decay $B^- \rightarrow [K^- \pi^+]_D h^-$, $B^- \rightarrow D_{fav} h^-$.  

The results are based on a data sample containing $275 \times 10^6 BB$ pairs, collected with the Belle detector at the KEKB asymmetric energy $e^+e^-$ storage ring [7] operating at the $Y(4S)$ resonance. 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 (TOF) scintillation counters, and an electromagnetic calorimeter composed 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 $K^0_L$ mesons and to identify muons. The detector is described in detail elsewhere [8]. Two different inner detector configurations were used. For the first sample of $152 \times 10^6 B\bar{B}$ pairs, a 2.0 cm radius beam pipe and a three-layer silicon vertex detector were used; for the latter $123 \times 10^6 B\bar{B}$ pairs, a 1.5 cm radius beam pipe, a four-layer silicon detector, and a small-cell inner drift chamber were used [9].

Neutral $D$ mesons are reconstructed by combining two oppositely charged tracks. For each track, information from ACC and TOF and specific ionization measurements from the CDC are used to determine a $K/\pi$ likelihood ratio $P(K/\pi) = L_K/(L_K + L_\pi)$, where $L_K$ and $L_\pi$ are kaon and pion likelihoods. We use the particle identification requirements $P(K/\pi) > 0.8$ for kaons and $P(K/\pi) < 0.2$ for pions. These requirements select kaons (pions) with momentum dependent efficiencies of 80%–95% (90%–95%) and pion (kaon) misidentification probabilities of 5%–20% (15%–20%). $D$ candidates are required to have an invariant mass within $\pm 2.5\sigma$ of the nominal $D$ mass: $1.850 < M(K\pi) < 1.879$ GeV/$c^2$. To improve the momentum determination, tracks from the $D$ candidate are refitted according to the nominal $D$ mass hypothesis and the reconstructed vertex position. $B$ mesons are reconstructed by combining $D$ candidates with primary charged hadron candidates. The signal is identified by two kinematic variables, the energy difference $\Delta E = E_D + E_h^- - E_{\text{beam}}$, and the beam-energy-constrained mass $M_{bc} = \sqrt{E_{\text{beam}}^2 - (\vec{p}_D + \vec{p}_h^-)^2}$, where $E_D$ is the energy of the $D$ candidate, $E_h$ is the energy of $h^-$, and $E_{\text{beam}}$ is the beam energy, all evaluated in the center-of-mass (c.m.) frame; $\vec{p}_D$ and $\vec{p}_h$ are the momenta of the $D$ and $h^-$ in the c.m. frame. Event candidates are accepted if they have $5.2 < M_{bc} < 5.3$ GeV/$c^2$ and $|\Delta E| < 0.2$ GeV. In the rare cases that there is more than one candidate in an event, we select the best candidate on the basis of a $\chi^2$ determined from the difference between the measured and nominal values of $M(K\pi)$ and $M_{bc}$.

To suppress the large background from the two-jetlike $e^+e^- \rightarrow q\overline{q}$ ($q = u, d, s, c$) continuum processes, variables that characterize the event topology are used. We construct a Fisher discriminant [10] of Fox-Wolfram moments called the Super-Fox-Wolfram (SFW) [11], where the Fisher coefficients are optimized by maximizing the separation between $B\bar{B}$ events and continuum events. Furthermore, $\cos\theta_B$, the cosine of the angle in the c.m. system of the $B$ flight direction with respect to the beam axis is also used to distinguish $B\bar{B}$ events from continuum events. These two independent variables, SFW and $\cos\theta_B$, are combined to form a likelihood ratio $R = L_{\text{sig}}/(L_{\text{sig}} + L_{\text{cont}})$, where $L_{\text{sig}}$ and $L_{\text{cont}}$ are likelihoods calculated from the SFW and $\cos\theta_B$ distributions of signal and continuum background events, respectively. We optimize the $R$ requirement by maximizing $S/\sqrt{S+N}$, where $S$ and $N$ denote the expected numbers of signal and background events in the signal region. For $B^- \rightarrow D_{\text{sup}}K^-$ ($B^- \rightarrow D_{\text{sup}}\pi^-$) we require $R > 0.85$ ($R > 0.75$), which retains 44.8% (57.6%) of the signal events and removes 96.2% (93.2%) of the continuum background.

For $B^- \rightarrow D_{\text{sup}}K^-$, there can be a contribution from $B^- \rightarrow D\pi^-$, $D \rightarrow K^+K^-$, which has the same final state and can peak under the signal. In order to reject these events, we veto events that satisfy $1.843 < M(KK) < 1.894$ GeV/$c^2$. The favored decay $B^- \rightarrow D_{\text{fav}}h^-$ can also cause a peaking background for the suppressed decay modes if both the kaon and the pion from the $D_{\text{fav}}$ decay are misidentified. Therefore, we veto events for which the invariant mass of the $K\pi$ pair is inside the $D$ mass window when the mass assignments are exchanged. After applying this veto, the residual background from $K\pi$ misidentification is found to be negligible. The three-body charmless decay $B^- \rightarrow K^+K^-\pi^-$ can peak inside the signal regions of $\Delta E$ and $M_{bc}$ for $B^- \rightarrow D_{\text{sup}}K^-$. This background is estimated from the $\Delta E$ distribution of events in a $D$ mass sideband, defined as $1.637 < M(K\pi) < 1.836$ GeV/$c^2$ and $1.893 < M(K\pi) < 2.093$ GeV/$c^2$. The estimated peaking background inside the $\Delta E$ signal region is $1.7 \pm 0.9$ events, which we subtract from the observed $B^- \rightarrow D_{\text{sup}}K^-$ yield. As a check, we estimate the expected background level from the measured $B^- \rightarrow K^+K^-\pi^-$ branching fraction [12]. Using this result, the expected background in our signal region is $2.1 \pm 0.6$ events, assuming that the $B^- \rightarrow K^+K^-\pi^-$ yield is uniformly distributed in phase space. For $B^- \rightarrow D_{\text{sup}}\pi^-$, the peaking background estimated from the $D$ mass sideband is consistent with zero.

The signal yields are extracted using binned maximum likelihood fits to the $\Delta E$ distributions of events in the $M_{bc}$ signal region ($5.27 < M_{bc} < 5.29$ GeV/$c^2$). Backgrounds from decays such as $B^- \rightarrow D\rho^-$ and $B^- \rightarrow D^+\pi^-$ are distributed in the negative $\Delta E$ region and make a small contribution to the signal region. The shape of this $B\bar{B}$ background is modeled with a smoothed histogram obtained from generic Monte Carlo (MC) samples. The continuum background populantes the entire $\Delta E$ region, and we model its shape with a linear function. The slope is determined from the $\Delta E$ distribution of the $M_{bc}$ sideband ($5.20 < M_{bc} < 5.26$ GeV/$c^2$). The $\Delta E$ fitting function is the sum of two Gaussians for the signal, the linear function for the continuum, and the smoothed histogram for the $B\bar{B}$ background distribution.

In the fit to the $\Delta E$ distribution of $B^- \rightarrow D_{\text{fav}}\pi^-$, the free parameters are the position, width, and area of the signal peak, and the normalizations of continuum and $B\bar{B}$
The signal peak are measured yield of the hypothesis for the prompt pion. The areas of signal and backgrounds. For the signal, the relative widths and areas of the two Gaussians are fixed from the signal MC sample. For the $B^- \rightarrow D_{_{s_{K^+}}}$ fit, the position and width of the signal peak are fixed from the $B^- \rightarrow D_{_{s_{K^+}}}$ fit results. To fit the feed across from $B^- \rightarrow D_{_{s_{K^+}}}$, we use a Gaussian shape where the left and right sides of the peak have different widths since the shift caused by a wrong mass assignment makes the shape asymmetric. The shape parameters of this function are fixed to values determined by the fit to the $B^- \rightarrow D_{_{s_{K^+}}}$ distribution using a kaon mass hypothesis for the prompt pion. The areas of signal and feed across from $B^- \rightarrow D_{_{s_{K^+}}}$, and the normalizations of continuum and $B\bar{B}$ backgrounds are floated. The fit results are shown in Fig. 2. The numbers of events for $B^- \rightarrow D_{_{s_{K^+}}}$ and $D_{_{s_{K^+}}}h^-$ and the statistical significances of the $B^- \rightarrow D_{_{s_{K^+}}}h^-$ signals are given in Table I. The statistical significance is defined as $\sqrt{-2 \ln (L_0/L_{\text{max}})}$, where $L_{\text{max}}$ is the maximum likelihood in the $\Delta E$ fit and $L_0$ is the likelihood when the signal yield is constrained to be zero. The uncertainty in the peaking background contribution is taken into account in the statistical significance calculation.

We next calculate ratios of product branching fractions, defined as

$$R_{Dh} \equiv \frac{B(B^- \rightarrow D_{sup} h^-)}{B(B^- \rightarrow D_{_{s_{K^+}}})} = \frac{N_{D_{sup} h^-}/\epsilon_{D_{sup} h^-}}{N_{D_{_{s_{K^+}}}} h^-}/\epsilon_{D_{_{s_{K^+}}}} h^-,$$

where $N_{D_{sup} h^-}(N_{D_{_{s_{K^+}}}} h^-)$ and $\epsilon_{D_{sup} h^-}(\epsilon_{D_{_{s_{K^+}}}} h^-)$ are the number of signal events and the reconstruction efficiency for the decay $B^- \rightarrow D_{sup} h^- (B^- \rightarrow D_{_{s_{K^+}}} h^-)$, and are given in Table I. We obtain

$$R_{DK} = [2.3^{+0.6}_{-0.1} \text{(stat)} \pm 0.1 \text{(syst)}] \times 10^{-2},$$

$$R_{D\pi} = [3.5^{+0.7}_{-0.7} \text{(stat)} \pm 0.2 \text{(syst)}] \times 10^{-3}.$$ 

Since the signal for $B^- \rightarrow D_{sup} K^-$ is not significant, we set an upper limit at the 90% confidence level (C.L.) of $R_{DK} < 4.4 \times 10^{-2}$, where we take the likelihood function as a single Gaussian with width given by the quadratic sum of statistical and systematic errors, and the area is normalized in the physical region of the positive branching fraction.

Most of the systematic uncertainties from the detection efficiencies and the particle identification cancel when taking the ratios, since the kinematics of the $B^- \rightarrow D_{sup} h^- (B^- \rightarrow D_{_{s_{K^+}}} h^-)$ processes are similar. The systematic errors are due to uncertainties in the yield extraction (4.7%–5.4%) and the efficiency difference between $B^- \rightarrow D_{sup} h^- (B^- \rightarrow D_{_{s_{K^+}}} h^-)$ (1.3%–1.7%). The uncertainties in the signal shapes and the $q\bar{q}$ background shapes are determined by varying the shape of the fitting function by $\pm 1\sigma$. The uncertainties in the $B\bar{B}$ background shapes are determined by fitting the $\Delta E$ distribution in the region $-0.07 < \Delta E < 0.20$ GeV ignoring the $B\bar{B}$ background contributions. The uncertainties in the efficiency differences are determined using signal MC calculations.

### Table I

<table>
<thead>
<tr>
<th>Mode</th>
<th>Product branching fraction from [13]</th>
<th>Efficiency (%)</th>
<th>Signal yield</th>
<th>Statistical significance</th>
<th>Measured product branching fraction</th>
<th>Upper limit (90% C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^- \rightarrow D_{sup} K^-$</td>
<td>$\cdots$</td>
<td>$12.9 \pm 0.2$</td>
<td>$8.5^{+6.0}_{-5.3}$</td>
<td>$2.3\sigma$</td>
<td>$(3.2^{+2.2}_{-2.0} \pm 0.2 \pm 0.5) \times 10^{-7}$</td>
<td>$6.3 \times 10^{-7}$</td>
</tr>
<tr>
<td>$B^- \rightarrow D_{sup} \pi^- (6.9 \pm 0.7) \times 10^{-7}$</td>
<td>$20.1 \pm 0.2$</td>
<td>$28.5^{+8.3}_{-7.4}$</td>
<td>$6.4\sigma$</td>
<td>$(6.6^{+18}_{-12.5} \pm 0.4 \pm 0.3) \times 10^{-7}$</td>
<td>$\cdots$</td>
<td></td>
</tr>
<tr>
<td>$B^- \rightarrow D_{<em>{s</em>{K^+}}} K^- (1.4 \pm 0.2) \times 10^{-5}$</td>
<td>$12.9 \pm 0.2$</td>
<td>$376^{+218}_{-211}$</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td></td>
</tr>
<tr>
<td>$B^- \rightarrow D_{<em>{s</em>{K^+}}} \pi^- (1.9 \pm 0.1) \times 10^{-4}$</td>
<td>$20.3 \pm 0.2$</td>
<td>$8181^{+94}_{-93}$</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td></td>
</tr>
</tbody>
</table>
This document contains a detailed analysis of a decay process involving the Belle detector, focusing on the study of the $B^\pm \rightarrow D_{\text{sup}} h^\pm$ decay. The analysis includes the extraction of partial rate asymmetries and the determination of $A_{DK}$ and $A_{Dh}$ asymmetry parameters. The analysis is based on a sample of $275 \times 10^6$ $B\bar{B}$ pairs collected with the Belle detector. The results are compared with previous searches and theoretical predictions, and the most precise current determination of $\phi_3$ is found to be $r_B < 0.27$.

The total systematic error is the sum in quadrature of the above uncertainties. Using the values of $R_{Dh}$ obtained above, we determine product branching fractions for $B^\pm \rightarrow D_{\text{sup}} h^\pm$ using

$$\mathcal{B}(B^\pm \rightarrow D_{\text{sup}} h^\pm) = \mathcal{B}(B^\pm \rightarrow D_{\text{lav}} h^\pm) \times R_{Dh}.$$  

The results are given in Table I. An additional uncertainty arises because of the error in the branching fraction of $B^\pm \rightarrow D_{\text{lav}} h^\pm$, which is taken from [13], which we quote as a separate systematic error. The uncertainties are statistics dominated. For the $B^\pm \rightarrow D_{\text{sup}} K^\pm$ product branching fraction, we set an upper limit at the 90% C.L. of $\mathcal{B}(B^\pm \rightarrow D_{\text{sup}} K^\pm) < 6.3 \times 10^{-7}$. For $B^\pm \rightarrow D_{\text{sup}} \pi^\pm$, our measured product branching fraction is consistent with expectation neglecting the contribution from $B^\pm \rightarrow D^0 \pi^\pm$.

The ratio $R_{DK}$ is related to $\phi_3$ by

$$R_{DK} = r_B^2 + r_D^2 + 2r_B r_D \cos \phi_3 \cos \delta,$$

where [13]

$$r_B \equiv \left| \frac{A(B^\pm \rightarrow D^0 K^\pm)}{A(B^\pm \rightarrow D^0 K^\mp)} \right|,$$

$$r_D \equiv \left| \frac{A(D^0 \rightarrow K^+ \pi^-)}{A(D^0 \rightarrow K^- \pi^+)} \right| = 0.060 \pm 0.003,$$

and $\delta_B$ and $\delta_D$ are the strong phase differences between the two $B$ and $D$ decay amplitudes, respectively. Using the above result, we obtain a limit on $r_B$. The least restrictive limit is obtained allowing $\pm 1\sigma$ variation on $r_D$ and assuming maximal interference ($\phi_3 = 0^\circ$, $\delta = 180^\circ$ or $\phi_3 = 180^\circ$, $\delta = 0^\circ$) and is found to be $r_B < 0.27$.

We search for partial rate asymmetries $A_{DK}$ in the $B^\pm \rightarrow D_{\text{sup}} h^\pm$ decay, fitting the $B^-$ and $B^+$ yields separately for each mode, where $A_{DK}$ is determined as

$$A_{DK} = \frac{\mathcal{B}(B^- \rightarrow D_{\text{sup}} h^-) - \mathcal{B}(B^+ \rightarrow D_{\text{sup}} h^+)}{\mathcal{B}(B^- \rightarrow D_{\text{sup}} h^-) + \mathcal{B}(B^+ \rightarrow D_{\text{sup}} h^+)}.$$

The peaking background for $B^\pm \rightarrow D_{\text{sup}} K^\pm$ is subtracted assuming no $CP$ asymmetry. The fit results are shown in Fig. 3 and Table II. We find

$$A_{DK} = 0.88^{+0.22}_{-0.23} \text{(stat)} \pm 0.06 \text{(syst)},$$

$$A_{Dh} = 0.30^{+0.22}_{-0.23} \text{(stat)} \pm 0.06 \text{(syst)},$$

where the systematic uncertainties arise from possible biases in the analysis algorithms (estimated from the $B^\pm \rightarrow D_{\text{lav}} \pi^\pm$ control sample to be 2.5%); uncertainties in the extraction of the $B^-$ and $B^+$ yields (estimated by varying fitting parameters by $\pm 1\sigma$ to be 4.9%); asymmetry in the particle identification efficiency of prompt kaons (estimated in [14] to be 0.6%). We assume no $CP$ asymmetry in the peaking background, and do not assign any systematic uncertainty from this source [15].

In summary, using $275 \times 10^6$ $B\bar{B}$ pairs collected with the Belle detector, we report studies of the suppressed decay $B^- \rightarrow D_{\text{sup}} h^-$ ($h = K, \pi$). We observe $B^- \rightarrow D_{\text{sup}} \pi^-$ for the first time, with a significance of 6.4$\sigma$. The size of the signal is consistent with the expectation based on measured branching fractions [13]. The significance for $B^- \rightarrow D_{\text{sup}} K^-$ is 2.3$\sigma$ and we set an upper limit on the ratio of $B$ decay amplitudes $r_B < 0.27$ at 90% confidence level. This result is consistent with previous searches [6], and with the measurement of $r_B$ in the decay $B^- \rightarrow DK^-$, $D \rightarrow K^0 \pi^+ \pi^-$ [16], which provides the most precise current determination of $\phi_3$.

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On leave from Nova Gorica Polytechnic, Nova Gorica.

[15] An assumption of 30% $CP$ asymmetry in the peaking background would lead to a shift of 5.5% in $A_{DK}$.