Search for $B^+ \to [K^+ \pi^\pm]_d K^+$ and Upper Limit on the $b \to u$ Amplitude in $B^+ \to D K^+$


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We search for $B^- \to [K^+ \pi^-]_D K^-$ decays, where $[K^+ \pi^-]_D$ indicates that the $K^+ \pi^-$ pair originates from the decay of a $D^0$ or $\bar{D}^0$. Results are based on $120 \times 10^6$ $Y(4S) \to B\bar{B}$ decays collected with the BABAR detector at SLAC. We set an upper limit on the ratio $R_{KB} = \frac{\Gamma(B^- \to [K^+ \pi^-]_D K^-) + \Gamma(B^- \to [K^+ \pi^-]_s K^-)}{\Gamma(B^- \to D^0 K^-)} < 0.026$ (90% C.L.). This constrains the amplitude ratio $r_B = |A(B^- \to \bar{D}^0 K^-)/A(B^- \to D^0 K^-)| < 0.22$ (90% C.L.), consistent with expectations. The small value
of $r_B$ favored by our analysis suggests that the determination of the Cabibbo-Kobayashi-Maskawa phase $\gamma$ from $B \to DK$ will be difficult.

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Following the discovery of $CP$ violation in $B$-meson decays and the measurement of the angle $\beta$ of the unitarity triangle [1] associated with the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix, focus has turned towards the measurements of the other angles $\alpha$ and $\gamma$. The angle $\gamma$ is $\arg(-V_{ub}^* V_{ud}/V_{cb}^* V_{cd})$, where $V_{ij}$ are CKM matrix elements; in the Wolfenstein convention [2], $\gamma = \arg(V_{ub}^*)$.

Several proposed methods for measuring $\gamma$ exploit the interference between $B^+ \to D^0 K^-$ and $B^+ \to \bar{D}^0 K^-$ (Fig. 1) which occurs when the $D^0$ and the $\bar{D}^0$ decay to common final states, as first suggested in Ref. [3].

Following the proposal in Ref. [4], we search for $B^+ \to \bar{D}^0 K^-$ followed by $\bar{D}^0 \to K^+ \pi^- \rho^+$, as well as the charge conjugate sequence, where the symbol $\bar{D}^0$ indicates either a $D^0$ or a $\bar{D}^0$. Here the favored $B$ decay followed by the doubly CKM-suppressed $D$ decay interferes with the suppressed $B$ decay followed by the CKM-favored $D$ decay. We use the notation $B^+ \to [h_i^+ h_j^-]_{D_h^\pm}^0$ (with each $h_i = \pi$ or $K$) for the decay chain $B^+ \to D^0 h_i^\pm$, $D^0 \to h_i^\pm h_j^-$. We also refer to $h_3$ as the bachelor $\pi$ or $K$. Then, ignoring $D$ mixing,

$$\mathcal{R}_{K^\pi}^\pm = \frac{\Gamma([K^\pm \pi^\pm]_D K^\pm)}{\Gamma([K^\pm \pi^\pm]_{D_0} K^\pm)} = r_B^2 + r_D^2 + 2r_B r_D \cos(\pm \gamma + \delta),$$

where

$$r_B = \frac{|A(B^+ \to \bar{D}^0 K^-)|}{|A(B^+ \to D^0 K^-)|}, \quad \delta = \delta_B + \delta_D,$$

$$r_D = \frac{|A(D^0 \to K^+ \pi^-)|}{|A(D^0 \to K^- \pi^-)|} = 0.060 \pm 0.003$$

[5], and $\delta_B$ and $\delta_D$ are strong phase differences between the two $B$ and $D$ decay amplitudes, respectively. The expression for $\mathcal{R}_{K^\pi}^\pm$ neglects the tiny contribution to the $[K^\pm \pi^\pm]_D K^\pm$ mode from the color-suppressed $B$ decay followed by the doubly CKM-suppressed $D$ decay.

Since $r_B$ is expected to be of the same order as $r_D$, $CP$ violation could manifest itself as a large difference between $\mathcal{R}_{K^\pi}^+$ and $\mathcal{R}_{K^\pi}^-$. Measurements of $\mathcal{R}_{K^\pi}^\pm$ are not sufficient to extract $\gamma$, since these two quantities are functions of three unknowns: $\gamma$, $r_B$, and $\delta$. However, they can be combined with measurements for other $D^0$ modes to extract $\gamma$ in a theoretically clean way [4].

The value of $r_B$ determines, in part, the level of interference between the diagrams of Fig. 1. In most techniques for measuring $\gamma$, high values of $r_B$ lead to better sensitivity. Since $\mathcal{R}_{K^\pi}^\pm$ depend quadratically on $r_B$, measurements of $\mathcal{R}_{K^\pi}^\pm$ can constrain $r_B$. In the standard model, $r_B = |V_{ub}^* V_{us}/V_{cb}^* V_{cd}| F_{cs} = 0.4 F_{cs}$, and $F_{cs} < 1$ accounts for the additional suppression, beyond that due to CKM factors, of $B^- \to \bar{D}^0 K^-$ relative to $B^- \to D^0 K^-$. Naively, $F_{cs} \approx 1$, which is the probability for the color of the quarks from the virtual $W$ in $B^- \to \bar{D}^0 K^-$ to match that of the other two quarks; see Fig. 1. Early estimates gave $F_{cs} = 0.22$ [6], leading to $r_B = 0.09$; however, recent measurements [7] of color-suppressed $b \to c$ decays $[B \to D^{(h)0}, h^0 = \pi^0, \rho^0, \omega, \eta, \eta']$ suggest that $F_{cs}$, and therefore $r_B$, could be larger, e.g., $r_B = 0.2$ [8]. A study by the Belle Collaboration of $B^+ \to D^0 K^+, D^0 \to K^0 \pi^+ \pi^-$ favors a large value of $r_B$: $r_B = 0.26^{+0.11}_{-0.15}$ [9].

Our results are based on 120 $\times 10^3$ $Y(4S) \to B \bar{B}$ decays, corresponding to an integrated luminosity of 109 fb$^{-1}$, collected between 1999 and 2003 with the BABAR detector [10] at the PEP-II B Factory at SLAC. A 12 fb$^{-1}$ off-resonance data sample, with a c.m. energy 40 MeV below the $Y(4S)$ resonance, is used to study continuum events, $e^+ e^- \to q\bar{q}$ ($q = u, d, s$, or $c$).

The event selection was developed from studies of simulated $B \bar{B}$ and continuum events, and off-resonance data. A large on-resonance data sample of $B^+ \to D^0 \pi^+$, $D^0 \to K^+ \pi^+$ events was used to validate several aspects of the simulation and analysis procedure. We refer to this mode and its charge conjugate as $B \to D \pi$.

Kaon and pion candidates in $B^+ \to [K \pi]_D K_{\pm}$ must satisfy $K$ or $\pi$ identification criteria that are typically 90% efficient, depending on momentum and polar angle. Misidentification rates are at the few percent level. The invariant mass of the $K \pi$ pair must be within 18.8 MeV (2.5$\sigma$) of the mean reconstructed $D^0$ mass. The remaining background from other $B^+ \to [h_i h_j]_{D_h^\pm}^0$ modes is eliminated by removing events where any $h_i^+ h_j^-$ pair, with any particle-type assignment except for the signal hypothesis for the $h_i h_j$ pair, is consistent with $D^0$ decay. We also reject $B$ candidates where the $D^0$ paired with a $\pi^0$ or $\eta^\pm$ in the event is consistent with $D^* \to D \pi$ decay.

FIG. 1. Feynman diagrams for $B^- \to D^0 K^-$ and $\bar{D}^0 K^-$. The latter is CKM and color suppressed with respect to the former.
After these requirements, backgrounds are mostly from continuum, mainly $e^+e^- \to c\bar{c}$, with $\bar{c} \to D^0 \to K^+\pi^-$ and $c \to D \to K^-$. These are reduced with a neural network based on nine quantities that distinguish continuum and $B\bar{B}$ events: (i) A Fisher discriminant based on the quantities $L_0 = \sum_p p_i$, and $L_2 = \sum_p \cos^2 \theta_i$, calculated in the c.m. frame. Here, $p_i$ is the momentum and $\theta_i$ is the angle with respect to the thrust axis of the $B$ candidate track and clusters not used to reconstruct the $B$. (ii) $|\cos \theta_p|$, where $\theta_p$ is the angle in the c.m. frame between the thrust axes of the $B$ and the detected remainder of the event. (iii) $\cos \theta_{\bar{B}}$, where $\theta_{\bar{B}}$ is the polar angle of the $B$ in the c.m. frame. (iv) $\cos \theta_D$, where $\theta_D$ is the decay angle in $D^0 \to K\pi$, i.e., the angle between the direction of the $K$ and the line of flight of the $D^0$ in the $D$ rest frame. (v) $\cos \theta\sqrt{p}$, where $\theta\sqrt{p}$ is the decay angle in $B \to \bar{D}\bar{K}$. (vi) The difference $\Delta Q$ between the sum of the charges of tracks in the $\bar{D}$ hemisphere and the sum of the charges of the tracks in the opposite hemisphere excluding the tracks used in the reconstructed $B$. For signal, $\langle \Delta Q \rangle = 0$, while for the $c\bar{c}$ background $\langle \Delta Q \rangle = 0.7 \times Q_B$, where $Q_B$ is the $B$ candidate charge. The $\Delta Q$ rms is 2.4. (vii) $Q_B \cdot Q_K$, where $Q_K$ is the sum of the charges of all kaons not in the reconstructed $B$. Many signal events have $Q_B \cdot Q_K \leq -1$, while most continuum events have no kaons outside of the reconstructed $B$, and hence $Q_K = 0$. (viii) the distance of the closest approach between the bachelor track and the trajectory of the $\bar{D}$. This is consistent with zero for signal events, but can be larger in $c\bar{c}$ events. (ix) The existence of a lepton ($\ell$ or $\mu$) and the invariant mass ($m_{K\ell}$) of the lepton and the bachelor $K$. Continuum events have fewer leptons than signal events. Moreover, most leptons in $c\bar{c}$ events are from $D \to K\ell\nu$, where $K$ is the bachelor kaon, so that $m_{K\ell} < m_D$.

The neural net is trained with simulated continuum and signal events. We find agreement between the distributions of all nine variables in simulation and in control samples of off-resonance data and of $B \to D\pi$. The neural net requirement is 66% efficient for signal, and rejects 96% of the continuum background. An additional requirement, $\cos \theta_D > -0.75$, rejects 50% of the remaining $B\bar{B}$ backgrounds and is 93% efficient for signal.

A $B$ candidate is characterized by the energy-substituted mass $m_{ES} = \sqrt{(E_0 + p_B)^2/E_0 - p_B^2}$ and the energy difference $\Delta E = E_B - \sqrt{\frac{E^2}{\gamma_3}}$, where $E$ and $p$ are energy and momentum, the asterisk denotes the c.m. frame, the subscripts 0 and $B$ refer to the $Y(4S)$ and $B$ candidates, respectively, and $s$ is the square of the c.m. energy. For signal events $m_{ES} = m_B$ within the resolution of about 2.5 MeV, where $m_B$ is the known $B$ mass.

We require $\Delta E$ to be within 47.8 MeV (2.5$\sigma$) of the mean value of $-4.1$ MeV found in the $B \to D\pi$ control sample. The yield of signal events is extracted from a fit to the $m_{ES}$ distribution of events satisfying all of the requirements discussed above.

Our selection includes contributions from backgrounds with $m_{ES}$ distributions peaked near $m_B$ (peaking backgrounds). We distinguish those with a real $D^0 \to K^+\pi^-$ and those without, e.g., $B^+ \to h^+h^-h^-$. The latter are estimated from events with $K^+\pi^-$ mass in a sideband of the $D^0$. The former are from $B \to D^0 \pi^-$, followed by the CKM-suppressed decay $D^0 \to K^+\pi^-$, with the bachelor $\pi$ misidentified as a $K$. These are estimated as $N_{peak}^{D^0} = r_{D^0}N_{D^0\pi}$, where $N_{D^0\pi}$ is the number of observed $B \to D\pi$ events with the $\pi$ misidentified as a $K$. The technique used to measure $N_{D^0\pi}$ is described below. Studies of simulated $B\bar{B}$ events indicate that other peaking background contributions are negligible.

Because of the small number of events, we combine the $B^+$ and $B^-$ samples. We define the quantity

$$R_{K^\pi} = \frac{\Gamma(B^- \to [K^+\pi^-]pK^-) + \Gamma(B^- \to [K^-\pi^+]pK^+)}{\Gamma(B^- \to [K^+\pi^-]pK^-) + \Gamma(B^- \to [K^-\pi^+]pK^+)}$$

assuming no CP violation in $[K^+\pi^-]pK^-$. We determine $R_{K^\pi} = cN_{sig}/N_{DK}$, where $N_{sig}$ is the number of $B^\pm \to [K^{\mp}\pi^{\pm}]pK^{\mp}$ signal events and $N_{DK}$ is the number of $B^\pm \to [K^{\mp}\pi^{\pm}]pK^{\mp}$ events, a mode that we denote by $B \to DK$. Most systematic uncertainties cancel in the ratio. The factor $c = 0.93 \pm 0.04$, determined from simulation, accounts for a difference in the event selection efficiency between the signal mode and $B \to DK$. This difference is mostly due to a correlation between the efficiencies of the $\cos \theta_D$ requirement and the $D^0$ veto constructed using the bachelor track and the oppositely charged track in the $[K\pi]$ pair. This correlation depends on the relative sign of the kaon and the bachelor track, and is different in the two modes.

The value of $R_{K^\pi}$ is obtained from a simultaneous unbinned maximum likelihood fit to four $m_{ES}$ and three $\Delta E$ distributions. These distributions are used to extract the parameters needed to calculate $R_{K^\pi}$ (e.g., $N_{sig}$) or to constrain the shapes of other distributions. The likelihood is expressed directly in terms of $R_{K^\pi}$.

The $m_{ES}$ distribution for signal candidates is fit to the sum of a threshold background function and a Gaussian. The number of events in the Gaussian is $N_{sig}^{D^0} + N_{peak}^{D^0}$, where $N_{peak}^{D^0}$ and $N_{peak}^{D^{\ast}\ell\ell}$ are the number of peaking background events with and without a real $\bar{D}^0$, respectively. The Gaussian parameters are constrained by the fit to the $m_{ES}$ distribution of $B \to DK$ events. The shape of the threshold function is constrained by fitting the $m_{ES}$ distribution of candidates in a sideband of $\Delta E (-125 < \Delta E < 200$ MeV, excluding the signal region). The $m_{ES}$ distribution for events passing all signal requirements, but with $K^\pm\pi^\mp$ mass in the sideband of the $\bar{D}^0$ is fit in the same manner. We estimate $N_{\ell\ell\ell\ell}$ from the Gaussian yield of this last fit, accounting for the different sizes of the signal and sideband $\bar{D}^0$ mass ranges. The $m_{ES}$
the likelihood, we set a Bayesian limit. The uncertainties are mostly statistical. From this like-
imation for the \( B \to DK \) candidates with the bachelor \( \pi \) mis-
identified as a \( K \). The ratio \( N_{DK}/N_{D\pi} \) is obtained by
fitting the \( \Delta E \) distribution for \( B \to DK \) candidate events with
\( m_{ES} > 5.27 \text{ GeV} \) [see Fig. 2(d)]. This is modeled as
the sum of a combinatoric background function, a double
Gaussian for the \( B \to D\pi \) background, and a Gaussian for
the \( B \to DK \) signal. The parameters of the Gaussians in
the \( \Delta E \) fit are constrained from fits to the \( \Delta E \) distributions
of well-identified \( B \to D\pi \) events with the bachelor
\( \pi \) assumed to be a \( \pi \) or a \( K \).

We find \( \mathcal{R}_{K\pi} = (4 \pm 12) \times 10^{-3} \), consistent with zero.

The number of signal, normalization, and peaking back-
ground events are \( N_{sig} = 1.1 \pm 3.0 \), \( N_{DK} = 261 \pm 22 \),
\( N_{peak}^{D} = r_{D}^{2} N_{D\pi} = 0.38 \pm 0.07 \), and \( N_{peak}^{hhh} = 0.4 \pm 1.1 \).

The uncertainties are mostly statistical. From this like-
elihood, we set a Bayesian limit \( \mathcal{R}_{K\pi} < 0.026 \) at the 90% confidence level (C.L.), assuming a constant prior probability for \( \mathcal{R}_{K\pi} > 0 \) (see Fig. 3).

In Fig. 4 we show the dependence of \( \mathcal{R}_{K\pi} \) on \( r_B \),
together with our limit. This is shown allowing a \( \pm 1\sigma \)
variation on \( r_D \), for the full range \( 0^\circ - 180^\circ \) for \( \gamma \) and \( \delta \), as
well as with the restriction \( 48^\circ < \gamma < 73^\circ \) suggested by
global CKM fits [11]. The least restrictive limit on \( r_B \) is
computed assuming maximal destructive interference:
\( \gamma = 0^\circ, \delta = 180^\circ \) or \( \gamma = 180^\circ, \delta = 0^\circ \). This limit is
\( r_B < 0.22 \) at 90% C.L.

In summary, we find no evidence for \( B^\pm \to [K^\pm \pi^\mp]\_D K^\pm \). We set a 90% C.L. limit on the ratio \( \mathcal{R}_{K\pi} \)
of rates for this mode and the favored mode \( B^\pm \to [K^\pm \pi^\mp]\_D K^\pm \). Our limit is
\( \mathcal{R}_{K\pi} < 0.026 \) at 90% C.L. With the most conservative assumption on the values
of \( \gamma \) and of the strong phases in the \( B \) and \( D \) decays, this
results in a limit on the ratio of the magnitudes of the
\( B^\pm \to \overline{D^0} K^\pm \) and \( B^\pm \to D^0 K^\pm \) amplitudes \( r_B < 0.22 \) at
90% C.L. Our analysis suggests that \( r_B \) is smaller than the
value reported by the Belle Collaboration, \( r_B = 0.26^ {+0.14}_{-0.15} \)
[9], but given the uncertainties the two results are not in
disagreement. A small value of \( r_B \) will make it diffi-

FIG. 3 (color online). Likelihood as a function of \( \mathcal{R}_{K\pi} \). The integral for \( 0 < \mathcal{R}_{K\pi} < 0.026 \) is 90% of the integral for
\( \mathcal{R}_{K\pi} > 0 \).
cult to measure $\gamma$ with other methods \cite{3,12} based on $B \to \bar{D}K$.

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