Search for $B^\pm \to [K^\mp \pi^\pm]_D K^\pm$ and upper limit on the $b \to u$ amplitude in $B^\pm \to D K^\pm$

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We search for $B^\pm \rightarrow (K^\mp \pi^\pm)\rho\rho$ decays, where $[K^\mp \pi^\pm]_D$ indicates that the $K^\mp \pi^\pm$ pair originates from the decay of a $D^0$ or $\overline{D}^0$. Results are based on $120 \times 10^6$ $\Upsilon(4S) \rightarrow BB$ decays collected with the BABAR detector at SLAC. We set an upper limit on the ratio

$$\mathcal{R}_{K} = \frac{\Gamma(B^+ \rightarrow [K^\mp \pi^\pm]_D K^\pm)}{\Gamma(B^+ \rightarrow [K^\mp \pi^\pm]_D K^\pm)} < 0.026 \ (90\% \ C.L.)$$

This constrains the amplitude ratio $r_B \equiv |A(B^+ \rightarrow \overline{D}^0 K^-)/A(B^+ \rightarrow D^0 K^-)| < 0.22 \ (90\% \ C.L.)$, consistent with expectations. The small value of $r_B$ favored by our analysis suggests that the determination of the CKM phase $\gamma$ from $B \rightarrow DK$ 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 $\alpha$ is $\arg(-V_{ub}V_{td}^*/V_{cb}V_{td})$, 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 $B^- \rightarrow D^0 K^-$ and $B^- \rightarrow \overline{D}^0 K^-$ (Fig. 1) which occurs when the $D^0$ and the $\overline{D}^0$ decay to common final states, as first suggested in Ref. [3].

![Feynman diagrams for $B^- \rightarrow D^0 K^-$ and $\overline{D}^0 K^-$. The latter is CKM- and color-suppressed with respect to the former.](image)

FIG. 1: Feynman diagrams for $B^- \rightarrow D^0 K^-$ and $\overline{D}^0 K^-$. The latter is CKM- and color-suppressed with respect to the former.

Following the proposal in Ref. [4], we search for $B^- \rightarrow \overline{D}^0 K^-$ followed by $\overline{D}^0 \rightarrow K^+ \pi^-$, as well as the charge conjugate sequence, where the symbol $\overline{D}^0$ indicates either a $D^0$ or a $\overline{D}^0$. 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 $B^- \rightarrow [h_1^+ h_2^-]_D h_3^-$, with each $h_i = \pi$ or $K$ for the decay chain $B^- \rightarrow D^0 h_3^-$, $\overline{D}^0 \rightarrow h_1^+ h_2^-$. We also refer to $h_3$ as the bachelor $\pi$ or $K$. Then, ignoring $D$ mixing,

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

where

$$r_B \equiv \frac{|A(B^- \rightarrow \overline{D}^0 K^-)|}{|A(B^- \rightarrow D^0 K^-)|}, \quad \delta \equiv \delta_B + \delta_D,$$

and $\delta_B$ and $\delta_D$ are strong phase differences between the two $B$ and $D$ decay amplitudes, respectively. The expression for $\mathcal{R}^{\pm}_{K}$ neglects the tiny contribution to the $[K^\mp \pi^\pm]_D K^\pm$ 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 $\mathcal{R}^{+}_{K}$ and $\mathcal{R}^{-}_{K}$. Measurements of $\mathcal{R}^{\pm}_{K}$ 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 $\overline{D}^0$ modes to extract $\gamma$ in a theoretically clean way [2].

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 $\mathcal{R}^{\pm}_{K}$ depend quadratically on $r_B$, measurements of $\mathcal{R}^{\pm}_{K}$ can constrain $r_B$. In the Standard Model, $r_B = |V_{ub}V_{cs}^*/V_{cb}V_{ts}| F_{cs} \approx 0.4 F_{cs}$, and $F_{cs} < 1$ accounts for the additional suppression, beyond that due to CKM factors, of $B^- \rightarrow \overline{D}^0 K^-$ relative to $B^- \rightarrow D^0 K^-$. Naively, $F_{cs} = 1/3$, which is the probability for the color of the quarks from the virtual $W$ in $B^- \rightarrow \overline{D}^0 K^-$ to match that of the other two quarks; see Fig. 1. Early estimates gave $F_{cs} \approx 0.22$, leading to $r_B \approx 0.09$; however, recent measurements [5] of color suppressed $b \rightarrow c$ decays ($B \rightarrow D^{(*)}h^0$; $h^0 = \pi^0, \rho^0, \omega, \eta, \eta'$) suggest that $F_{cs}$, and therefore $r_B$, could be larger, e.g., $r_B \approx 0.2$ [8]. A study by the Belle collaboration [9] favors a large value of $r_B$: $r_B = 0.26^{+0.11}_{-0.15}$.

Our results are based on $120 \times 10^6 \Upsilon(4S) \rightarrow BB$ 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 CM energy 40 MeV below the $\Upsilon(4S)$ resonance, is used to study continuum events, $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s$, or $c$).

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

Kaon and pion candidates in $B^\pm \rightarrow [K\pi]_D K^\pm$ 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 (2.5σ) of the mean reconstructed $D^0$ mass. The remaining background from other $B^\pm \rightarrow [h_1 h_2]_{0\pi\pi}$ modes is eliminated by removing events where any $h_1^+ h_2^-$ pair, with any particle-type assignment except for the signal hypothesis for the $h_1 h_2$ pair, is consistent with $D^0$ decay. We also reject $B$ candidates where the $D^0$ paired with a $\pi^0$ or $\pi^\pm$ in the event is consistent with $D^\star \rightarrow D\pi$ decay.

After these requirements, backgrounds are mostly from continuum, mainly $e^+e^- \rightarrow c\bar{c}$, with $c \rightarrow D^0 \rightarrow K^+\pi^-$ and $c \rightarrow D \rightarrow K^-$. 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 $L_0 = \sum_i p_i$ and $L_2 = \sum_i p_i \cos^2 \theta_i$ calculated in the CM frame. Here, $p_i$ is the momentum and $\theta_i$ is the angle with respect to the thrust axis of the $B$ candidate of tracks and clusters not used to reconstruct the $B$. (ii) $|\cos \theta_T|$, where $\theta_T$ is the angle in the CM frame between the thrust axes of the $B$ and the detected remainder of the event. (iii) $\cos \theta_B$, where $\theta_B$ is the polar angle of the $B$ in the CM frame. (iv) $\cos \theta_D^0$ which is the decay angle in $D^0 \rightarrow K\pi$, i.e., the angle between the direction of the $K$ and the line of flight of the $D^0$ in the $D^0$ rest frame. (v) $\cos \theta_D^0$, where $\theta_D^0$ is the decay angle in $B \rightarrow D^0 K$. (vi) the difference $\Delta Q$ between the sum of the charges of tracks in the $D^0$ 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 $\langle \Delta Q \rangle \approx 1 \times Q_B$, 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 closest approach between the bachelor track and the trajectory of the $D^0$. This is consistent with zero for signal events, but can be larger in $c\bar{c}$ events. (ix) the existence of a lepton ($e$ or $\mu$) and the invariant mass ($m_{K\ell\nu}$) 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 $D \rightarrow K\ell\nu$, where $K$ is the bachelor kaon, so that $m_{K\ell\nu} < m_D$.

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 $B \rightarrow D\pi$. The neural net requirement is 66% efficient for signal, and rejects 96% of the continuum background. An additional requirement, $\cos \theta_D^0 > -0.75$, 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 $m_{ES} \equiv \sqrt{\left(\frac{E}{2} + \vec{p}_B \cdot \vec{p}_B\right)^2/E_B^2 - p_B^2}$ and energy difference $\Delta E \equiv E_B - \frac{1}{2}\sqrt{s}$, where $E$ and $p$ are energy and momentum, the asterisk denotes the CM frame, the subscripts 0 and $B$ refer to the $\Upsilon(4S)$ and $B$ candidate, respectively, and $s$ is the square of the CM 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 (2.5σ) of the mean value of $-4.1$ MeV found in the $B \rightarrow D\pi$ 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 $D^0 \rightarrow K^+\pi^\pm$ and those without, e.g., $B^+ \rightarrow h^+ h^- h^-$. The latter are estimated from events with $K^+\pi^\pm$ mass in a sideband of the $D^0$. The former are from $B^- \rightarrow D^0\pi^-$, followed by the CKM-suppressed decay $D^0 \rightarrow K^+\pi^-$, with the bachelor $\pi$ misidentified as a $K$. These are estimated as $N_{peak}^D = r_D^2 N_{D\pi}$, where $N_{D\pi}$ is the number of observed $B \rightarrow D\pi$ events with the $\pi$ misidentified as a $K$. The technique used to measure $N_{D\pi}$ 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

$$\mathcal{R}_{K\pi} = \frac{\Gamma(B^- \rightarrow [K^+\pi^-]_D K^-) + \Gamma(B^+ \rightarrow [K^-\pi^+]_D K^+)}{\Gamma(B^- \rightarrow [K^-\pi^+]_D K^-) + \Gamma(B^+ \rightarrow [K^+\pi^-]_D K^+)}$$

assuming no $CP$ violation in $[K^+\pi^\pm]_D K^\mp$.

We determine $\mathcal{R}_{K\pi} = c N_{sig}/N_{DK}$, where $N_{sig}$ is the number of $B^\pm \rightarrow [K^+\pi^\mp]_D K^\mp$ signal events and $N_{DK}$ is the number of $B^\pm \rightarrow [K^\mp\pi^\pm]_D K^\pm$ events, a mode which we denote by $B \rightarrow DK$. 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 $B \rightarrow DK$. This difference is mostly due to a correlation between the efficiencies of the $\cos \theta_D^0$ 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 $\mathcal{R}_{K\pi}$ 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 $\mathcal{R}_{K\pi}$ (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 centered at $m_B$. The $m_{ES}$ distribution for events passing all signal requirements, but with $m_{ES}$ in a sideband of $|\Delta E| < 4.1$ MeV, is also fit to a Gaussian and a threshold function. The number of events in the Gaussian is $N_{sig} + N_{peak}^D + N_{peak}^{hh}$, where $N_{peak}^D$ and $N_{peak}^{hh}$ are the number of peaking background events with and without a real $D^0$, respectively. The Gaussian parameters are constrained by the fit to the $m_{ES}$ distribution of candidates in a sideband of $|\Delta E| < 200$ MeV, excluding the signal region. The $m_{ES}$ distribution for events passing all signal requirements, but with $K^{+}\pi^{\pm}$ mass in the sideband of the $D^0$ is fit in the same manner. We estimate $N_{peak}^{hh}$ from the Gaussian yield of the last fit, accounting for the different sizes of the signal and sideband $D^0$ mass ranges. The $m_{ES}$ distributions for signal and $D^0$ sideband candidates are shown in Fig. 2a,b.

The $m_{ES}$ distribution for $B \to D K$ candidates with $|\Delta E| < 48.7$ MeV (see Fig. 2c) is also fit to a Gaussian and a threshold function. The number of events in the Gaussian is $N_{DK} + N_{D\pi}$, where, as previously defined, $N_{DK}$ is the number of $B \to D K$ events and $N_{D\pi}$ is the number of $B \to D \pi$ events with the bachelor $\pi$ misidentified as a $K$. The ratio $N_{DK}/N_{D\pi}$ is obtained by fitting the $\Delta E$ distribution for $B \to D K$ candidate events with $m_{ES} > 5.27$ GeV (see Fig. 2d). 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 $B \to D K$ 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 $R_{K\pi} = (4 \pm 12) \times 10^{-3}$, consistent with zero. The number of signal, normalization, and peaking background events are $N_{sig} = 1.1 \pm 3.0$, $N_{DK} = 261 \pm 22$, and $N_{peak}^{hh} = 0.38 \pm 0.07$, and $N_{peak}^{hh} = 0.4 \pm 1.1$. The uncertainties are mostly statistical. From the likelihood, we set a Bayesian limit $R_{K\pi} < 0.026$ at the 90% confidence level (C.L.), assuming a constant prior probability for $R_{K\pi} > 0$ (see Fig. 3).

In Fig. 4 we show the dependence of $R_{K\pi}$ on $r_B$, together with our limit. This is shown allowing a $\pm 1\sigma$ variation on $r_B$, for the full range $0^\circ < \gamma < 180^\circ$ and $\delta$, as well as with the restriction $48^\circ < \gamma < 73^\circ$ suggested by global CKM fits. 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 $B^\pm \to [K^{\mp}\pi^{\pm}] D K^{\mp}$. We set a 90% C.L. limit on the ratio $R_{K\pi}$ of rates for this mode and the favored mode $B^\pm \to [K^{\mp}\pi^{\pm}] D K^{\mp}$. Our limit is $R_{K\pi} < 0.026$ 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 $B^- \to D^0 K^-$ and $B^- \to D^0 K^-$ 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, \( r_B = 0.26^{+0.11}_{-0.15} \), but given the uncertainties the two results are not in disagreement. A small value of \( r_B \) will make it difficult to measure \( \gamma \) with other methods [3][12] based on \( B \to \bar{D}K \).

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