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A Study of $b \to c$ and $b \to u$ Interference in the Decay $B^- \to [K^+\pi^-]_D K^{*-}$

B. Aubert,1 R. Barate,1 D. Boutigny,1 F. Coudere,1 Y. Karyotakis,1 J. P. Lees,1 V. Poirean,1 V. Tisserand,1 A. Zghiche,1 E. Graugues,2 A. Palano,3 M. Pappagallo,3 A. Pompli,3 J. C. Chen,4 N. D. Qi,4 G. Rong,4 P. Wang,4 Y. S. Zhu,4 G. Eigen,5 I. Ofte,5 B. Stugu,5 G. S. Abrams,6 M. Battaglia,6 A. B. Breon,6 D. N. Brown,6 J. Button-Shaffer,6 R. N. Cahn,6 E. Charles,6 C. T. Day,6 M. S. Gill,6 A. V. Gritsan,6 Y. Groyman,6 R. G. Jacobsen,6 R. W. Kadel,6 J. Kadyk,6 L. T. Kerth,6 Yu. G. Kolomensky,6 G. Kukartsev,6 G. Lynch,6 L. M. Mir,6 P. J. Oddone,6 T. J. Orimoto,6 M. Pripstein,6 N. A. Roe,6 M. T. Roman,6 W. A. Wenzel,6 M. Barrett,7 K. E. Ford,7 T. J. Harrison,7 A. J. Hart,7 C. M. Hawkes,7 S. E. Morgan,7 A. T. Watson,7 M. Fritsch,8 K. Goetzen,8 T. Held,8 H. Koch,8 B. Lewandowski,8 M. Pelizaeus,8 K. Peters,8 T. Schroeder,8 M. Steinke,8 J. T. Boyd,9 J. P. Burke,9 N. Chevalier,9 W. N. Cottingham,9 T. Cuhadar-Donzelsch,10 B. G. Fulsom,10 C. Hearty,10 N. S. Knecht,10 T. S. Mattison,10 J. A. 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Using a sample of $232 \times 10^6 \, \Upsilon(4S) \rightarrow B\bar{B}$ events collected with the \babar{} detector at the PEP-II B-factory we study the decay $B^- \rightarrow [K^+\pi^-]_D K^{*-}$ where the $K^+\pi^-$ is either from a Cabibbo-favored $D_0$ decay or doubly-suppressed $D_s$ decay. We measure two observables that are sensitive to the CKM angle $\gamma$; the ratio $R$ of the charge-averaged branching fractions for the suppressed and favored decays; and the charge asymmetry $A$ of the suppressed decays:

$$R = 0.046 \pm 0.031(\text{stat.}) \pm 0.008(\text{syst.})$$

$$A = -0.22 \pm 0.61(\text{stat.}) \pm 0.17(\text{syst.}).$$

PACS numbers: 13.25.Hw, 14.40.Nd

An important feature of the standard model is that it accommodates CP violation through the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix $V$. The self consistency of this mechanism can be checked by overconstraining the associated unitarity triangle. In this paper we concentrate on the angle $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ by studying $B$-meson decay channels where $b \rightarrow c\bar{u}s$ and $b \rightarrow u\bar{c}s$ tree amplitudes interfere. We use a technique suggested by Amsler, Duniertz and Soni (ADS) where the final state $B^- \rightarrow K^+\pi^- K^*(892)^-$ can be reached from two amplitudes, $B^- \rightarrow D_0^0 K^{*-}$ followed by the doubly-Cabibbo-suppressed decay $D_0^0 \rightarrow K^+\pi^-$, and $B^- \rightarrow D_s^0 K^{*-}$ followed by the Cabibbo-favored decay $D_s^0 \rightarrow K^+\pi^-$. The size of the interference between these two amplitudes depends on the CKM angle $\gamma$ as well as the CP-conserving relative strong phases $\delta_B$ and $-\delta_D$, and the ratios $r_B$ and $r_D$ of suppressed and favored amplitude magnitudes in $B$- ($A(B^- \rightarrow D_0^0 K^{*-})$ and $A(B^- \rightarrow D_s^0 K^{*-})$), and $D$- ($A(D^0 \rightarrow K^+\pi^-)$ and $A(D^0 \rightarrow K^-\pi^+)$) decays. We define two measurable quantities, $R$ and $A$, as follows:

$$R = \frac{\Gamma(B^- \rightarrow [K^+\pi^-]^0_D K^{*-}) + \Gamma(B^+ \rightarrow [K^-\pi^+]^0_D K^{*-})}{\Gamma(B^- \rightarrow [K^+\pi^-]^0_D K^{*-}) + \Gamma(B^+ \rightarrow [K^-\pi^+]^0_D K^{*-})}$$

$$A = \frac{\Gamma(B^- \rightarrow [K^+\pi^-]^0_D K^{*-}) - \Gamma(B^+ \rightarrow [K^-\pi^+]^0_D K^{*-})}{\Gamma(B^- \rightarrow [K^+\pi^-]^0_D K^{*-}) + \Gamma(B^+ \rightarrow [K^-\pi^+]^0_D K^{*-})}.$$ 

The notation $[K^+\pi^-]^0_D$ indicates that these particles are neutral $D$-meson ($D^0$ or $\bar{D}^0$) decay products. Neglecting the very small effect of $D^0\bar{D}^0$ mixing as justified in ref. 3, $R$ and $A$ are related to $\gamma$, the strong phases, $r_B$, and $r_D$ by

$$R = r_D^2 + r_B^2 + 2r_D r_B \cos(\delta_B + \delta_D) \cos \gamma,$$

$$A = 2r_D r_B \sin(\delta_B + \delta_D) \sin \gamma / R.$$  

In the above equations only $r_D$ has been measured: $r_D^2 = 0.00362 \pm 0.00029$. Estimates for $r_B$ are in the range $0.1 \leq r_B \leq 0.3$. Because there are more unknowns than measurable quantities, determining $R$ and $A$ does not uniquely determine $\gamma$. However, the $R$ and $A$ measured here can be used in combination with a similar technique proposed by Gronau, London, and Wyler (GLW) to provide constraints on $r_B$ and eventually $\gamma$.

Other methods sensitive to $\gamma$ rely on the analysis of three-body $D^0$ final states.

This analysis uses data collected near the $\Upsilon(4S)$ resonance with the \babar{} detector at the PEP-II storage ring. The data set consists of $211 \, \text{fb}^{-1}$ collected at the peak of the $\Upsilon(4S)$ ($232 \times 10^6 \, \text{B}\bar{\text{B}}$ pairs) and $20.4 \, \text{fb}^{-1}$ below the resonance peak (off-peak data).

The \babar{} detector uses a five-layer double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) to measure the trajectories of charged particles. Both the SVT and DCH are located inside a 1.5-T solenoidal magnetic field. Photons are detected by means of a CsI(Tl) crystal calorimeter also located inside the magnet. Charged particle identification is determined from information provided by a ring-imaging Cherenkov device (DIRC) in combination with ionization measurements ($dE/dx$) from the tracking detectors.

The \babar{} detector’s response to various physics processes as well as varying beam and environmental conditions is modeled with GEANT4 based software.

The decay $B^- \rightarrow D_0^0 K^{*-}$ is reconstructed in final states where the $K^{*-}$ decays to $K_0^0\pi$ followed by $K_0^0 \rightarrow \pi^+\pi^-$ and the $D^0$ decays into a charged kaon and pion. The analysis begins with the selection of $K_0^0$ candidates from oppositely charged tracks assumed to be pions. The invariant mass of the $K_0^0$ candidate is required to be within $10 \, \text{MeV}/c^2$ (about three standard deviations) of the nominal $K_0^0$ mass $2$. The $K_0^0$ candidate is required to travel at least four times farther than the standard deviation of its decay length. Its flight direction and decay length must be consistent with those of a $K_0^0$ originating from the interaction point. The momentum of a $K_0^0$ candidate meeting these criteria is then recalculated with a mass and vertex constraint. Next, a $K_0^0$ is paired with a charged track, assumed to be a pion, and the combination is constrained to come from the interaction point. The pair is kept for further study if its invariant mass is within $55 \, \text{MeV}/c^2$ of the nominal $K^*$ mass $2$. Finally, since the $K^*$ from a $B^- \rightarrow D_0^0 K^{*-}$ decay is polarized, we require $|\cos \theta_H| \geq 0.4$ where $\theta_H$ is the angle in the $K^*$ rest frame between the daughter pion and the parent $B$ momentum vector. This helicity-angle requirement helps discriminate $B$ mesons from combinatorial background (mostly $e^+e^- \rightarrow q\bar{q}$ continuum events; $q \in \{u, d, s, c\}$) as the former have a $\cos^2 \theta_H$ distribution while that of the
To perform the measurement, we reconstruct Cabibbo-favored $D^0 \to K^- \pi^+$ and doubly-Cabibbo-suppressed $D^0 \to K^+ \pi^-$ candidates. Candidates that have an invariant mass within 18 MeV/$c^2$ (2.5 standard deviations) of the nominal $D^0$ mass $\sqrt{2}$ are kept for further study. We also select $D^0 \to K^- \pi^+ \pi^0$ and $D^0 \to K^- \pi^+ \pi^- \pi^-$ candidates to define various signal distributions discussed later in this paper. Loose particle identification criteria are imposed on the charged particles of all studied decay channels. Pairs of photons with a total energy greater than 200 MeV and an invariant mass in the range $125 \leq m_{\gamma\gamma} \leq 145$ MeV/$c^2$ are combined to form $\pi^0$ candidates that are used to calculate the cosine of the angle between the nominal $\pi^0$ mass $\sqrt{2}$. Loose kinematic criteria are used to select the three- and four-body candidates.

Suppression of backgrounds from $e^+e^- \to q\bar{q}$ continuum events is achieved by using event shape and angular variables. Global event-shape variables are used to eliminate events with jet-like topology, a signature of $\tau\nu\mu$ events is achieved by using event shape and angular variables. The thrust angle of a $B$-meson candidate is required to satisfy $|\cos \theta_T| \leq 0.9$, where $\theta_T$ is the angle between the thrust axis of the $B$-meson and that of the rest of the event.

To further reduce the $q\bar{q}$ contribution to our data sample a neural network (NN) is used. The variables used in the neural network consist of the angular moments $L^0$ and $L^2$ defined in Ref. 10, the ratio $R_2 = H_2/H_0$ of Fox-Wolfram moments 11, the $\chi^2$ of the $B$-meson vertex fit, the cosine of the angle between the $B$ candidate momentum vector and the beam axis ($\cos \theta_B$), $\cos \theta_T$ (defined above), and the cosine of the angle between a $D^0$ daughter momentum vector in the $D^0$ rest frame and the direction of the $D^0$ in the $B$-meson rest frame ($\cos \theta_{H^0}(D^0)$). The NN is trained with signal Monte Carlo events and continuum data collected below the $T(4S)$ (off-peak data). The NN is then cross-checked with an independent set of signal Monte Carlo events. Finally, we verify that the NN has a consistent output for off-peak data and $q\bar{q}$ Monte Carlo events. The separation between signal and continuum background is shown in Fig. 1. We select candidates with neural network output above 0.8. Our event selection is optimized to minimize the statistical error on the signal yield, determined using simulated signal and background events.

We identify $B$-meson candidates using two nearly independent variables that take advantage of the well-defined beam energy and the known kinematics of $T(4S)$ decay: the beam-energy-substituted mass $m_{ES} = \sqrt{s/2 + p_0 \cdot p_B / E_0^2 - p_B^2}$ and the energy difference $\Delta E = E_B - \sqrt{s/2}$ where the subscripts 0 and $B$ refer to the $e^+e^-$ system and $B$-meson candidate, respectively; $\sqrt{s}$ is the $e^+e^-$ center-of-mass (CM) energy and the asterisk labels the CM frame. The $m_{ES}$ distribution for signal events is well represented by a Gaussian function with mean centered at the known mass of the $B^-$. and width 2.76 MeV/$c^2$. The $\Delta E$ distribution for signal events is described by a Gaussian function centered at zero with a width that varies from 11 to 13 MeV among the different final states. These quantities are measured in the data from $B^- \to D^0 K^*$ with Cabibbo-favored $D^0$ decays. For this analysis signal events must satisfy $|\Delta E| \leq 25$ MeV.

The efficiency to detect a $B^- \to D^0 K^*$ signal event where $D^0 \to K\pi$, after all criteria are imposed, is $(9.6\pm0.1)\%$. This efficiency is the same for $D^0 \to K^- \pi^+$ and $D^0 \to K^+ \pi^-$. There are multiple candidates in 12% of the events. In such cases the candidate with the smallest $|\Delta E|$ is selected for further study. According to Monte Carlo simulation, this is the correct candidate 88% of the time.

We study various potential sources of background using a combination of Monte Carlo simulation and data events. Two sources of background are identified in large samples of simulated $BB$ events. One source is $D^0 K^0_\pi$ production where the $K^0_\pi$ is non resonant and has an invariant mass in the $K^{*0}$ mass window. This background is discussed later in this paper. The second background (peaking background) includes instances where a favored decay (i.e. $B^- \to [K^- \pi^+]_B K^*$) contributes to fake candidates for the suppressed decay (i.e. $B^+ \to [K^- \pi^+]_D K^{*+}$). The most common way for this to occur is for a $\pi^+$ from the rest of the event to be substituted for the $\pi^-$ in the $K^{*+}$ candidate. Other sources of peaking background include double particle-identification failure in signal events that results in $D^0 \to K^- \pi^-$ being reconstructed as $D^0 \to \pi^- K^+$, or the kaon from the $D^0$ being interchanged with the charged pion from the $K^*$. From a detailed Monte Carlo study the total size of this background is estimated to be $1.4\pm0.2$ events. We also

![FIG. 1: The result of the neural network training and verification (see text). The training samples are shown as histograms. The signal (Monte Carlo simulation) is the shaded histogram peaking to the right; the background (off-peak data recorded 40 MeV below the resonance) is the histogram with a peak near 0. The data samples used to check the NN are overlaid as data points. The vertical bar and the arrow indicate the requirement used to select signal candidates.](image-url)
verify with the Monte Carlo simulation that the charmless decays with the same final state as the signal (e.g., $B^- \rightarrow K^*^- K^- \pi^+$) are not a significant background for this analysis.

Signal yields are determined from an unbinned extended maximum likelihood fit to the $m_{ES}$ distribution in the range $m_{ES} \geq 5.2$ GeV/$c^2$. A Gaussian function ($\mathcal{G}$) is used to describe all signal shapes while the combinatorial background is modeled with an ARGUS [12] threshold function. This function’s shape is determined by one parameter $\xi$ while a second parameter, $E_{\text{max}} = \sqrt{s}/2$, (fixed at 5.2901 GeV/$c^2$) is the maximum mass for pair-produced $B$-mesons given the collider beams energies. For a probability distribution function ($PDF$) we use $a \cdot A + b \cdot \mathcal{G}$ where $a$ is the number of background events and $b$ the number of signal events. We correct $b$ for the peaking background previously discussed (1.4±0.2 events). The mean and width of $\mathcal{G}$ and the value of $\xi$ are determined by an initial fit to all $B^- \rightarrow D^0K^*$ candidates where the $D^0$ decays into the Cabibbo-favored channels $K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^+\pi^-$. 

In Fig. 2 we show the results of a simultaneous fit to $B^- \rightarrow [K^+\pi^-]_D K^{*-}$ and $B^- \rightarrow [K^-\pi^+]_D K^{*-}$ candidates that satisfy all selection criteria. We call wrong-(right-) sign decays those where the $K^*$ and the kaon have opposite (same) strangeness. It is in the wrong-sign decays that the interference we study takes place. Therefore in Fig. 3 we display the same fit separately for the wrong-sign decays of the $B^+$ and the $B^-$ mesons. The results of the maximum likelihood fit are $R = 0.046\pm0.031$, $A = -0.22 \pm 0.61$, and $91.2 \pm 9.7 B^- \rightarrow [K^-\pi^+]_D K^{*-}$ right-sign events. Expressed in terms of the wrong-sign yield, the fit result is $4.2 \pm 2.8$ wrong-sign events. The errors are statistical only. The correlation between $R$ and $A$ is insignificant.

In Table I we summarize the systematic errors relevant to this analysis. Since both $R$ and $A$ are ratios of similar quantities most potential sources of systematic errors cancel. The estimate for the detection-efficiency asymmetry is obtained from a sample of $B^- \rightarrow D^0\pi^-$ events. Here a charge asymmetry of $A_{ch} = (-1.9\pm0.8)^%$ is measured. We add linearly the central value and one-standard deviation in the most conservative direction to assign a systematic error of $\delta A_{ch} = \pm 0.027$ to the $A$ measurement. To a good approximation the systematic error in $R$ due to this source can be shown to be given by $\delta R = R \cdot A \cdot \delta A_{ch}$, with $A$ the previously determined
We also quote the results in terms of two other variables: 

\[ R = 0.046 \pm 0.031 \text{(stat.)} \pm 0.008 \text{(syst.)}, \]

\[ A = -0.22 \pm 0.61 \text{(stat.)} \pm 0.17 \text{(syst.)}. \]

We also quote the results in terms of two other variables:

\[ R (1 + A) = 0.036 \pm 0.042 \pm 0.010, \]

\[ R (1 - A) = 0.056 \pm 0.045 \pm 0.012. \]

They may be of use in combining \( \gamma \)-sensitive measurements from the GLW and ADS methods, and analyses exploiting three-body \( D^0 \) decays. The effect of the non resonant \( K^0_S \pi^- \) background gives the dominant contribution to the systematic uncertainties, \( \pm 0.009 \) on both quantities.

In order to extract information on \( r_B \) and \( \gamma \) we combine the above measurements of \( R \) and \( A \) with measurements of similar quantities, \( R_{CP \pm}, A_{CP \pm} \), from \( B \to D^{0}_{CP}K^{*-0} \) using the method suggested in Ref. [13], in which the \( D^0 \) decays to \( CP \) eigenstates are exploited. A frequentist statistical approach [14] is used. A \( \chi^2 \) is formed from the differences between the measured and theoretical values, and the covariance matrix of the six measured variables. We restrict \( r_B \) to values between 0 and 1.3 and allow \( \gamma \) to vary between 0 and 180° for all possible values of \( (\delta_B + \delta_B) \) between 0 and 360°. We call \( \chi^2_{\text{min}} \) the minimum \( \chi^2 \) for the whole parameter space. We then scan the \( r_B \) range: for each value of \( r_B \) we minimize the \( \chi^2 \) across the reduced parameter space (where \( r_B \) is fixed), and find \( \chi^2_m \). We use \( \Delta \chi^2 = \chi^2_m - \chi^2_{\text{min}} \) to compute the confidence level of \( r_B \) assuming Gaussian uncertainties. Figure 4 shows the confidence level resulting from this \( r_B \) scan. Combining the ADS and GLW results we find

\[ r_B = 0.28^{+0.06}_{-0.10}. \]

In a similar fashion, we show the confidence level for the \( \gamma \) scan in Fig. 5. The interval \( 75^\circ \leq \gamma \leq 105^\circ \) is disfavored at the two-standard deviation level.

In summary we present the first measurements of yields from \( B^- \to [K^+\pi^-]_D K^{*-} \) decays. By exploring the behavior of the likelihood function close to its maximum, we determine that the statistical significance for \( R \) to differ from zero is at the two-standard deviation level. As seen on Fig. 4 this (ADS) result narrows the allowed \( r_B \) range previously obtained with the GLW method [13]. The constraint the ADS method provides on \( \gamma \) is weak.

| Source                     | \( \delta R \) | \( \delta A \) |
|----------------------------|---------------|---------------|
| Detection asymmetry        | \( \pm 0.0003 \pm 0.027 \) |
| Peaking background         | \( \pm 0.002 \pm 0.043 \) |
| Non resonant \( K^0_S \pi^- \) background | \( \pm 0.0073 \pm 0.126 \) |
| Shape of \( m_{ES} \) distribution | \( \pm 0.0023 \pm 0.108 \) |
| Total systematic error     | \( \pm 0.008 \pm 0.174 \) |

FIG. 4: Constraints on \( r_B \). The BABAR \( B^- \to D_{CP}K^{*-} \) (GLW) [1] result is combined with this analysis. The dashed (dotted) curve shows 1 minus the confidence level to exclude the abscissa-value as a function of \( r_B \) derived from the GLW (ADS) only measurements. When both the GLW and ADS results are combined the curve above the shaded area is obtained. Horizontal lines show the exclusion limits at the 1, 2 and 3 standard deviation levels.
FIG. 5: 1 minus exclusion confidence level curve for $\gamma$ obtained from the BABAR $B^- \to D_{CP}K^{*-}$ (GLW) result combined with this analysis. The graphical conventions are described in the caption of Fig. 4.

with the present data sample.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from CONACyT (Mexico), A. P. Sloan Foundation, Research Corporation, and Alexander von Humboldt Foundation.

* Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy
† Also with Università della Basilicata, Potenza, Italy
‡ Deceased

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