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Evidence for Direct CP Violation in the Measurement of the Cabbibo-Kobayashi-Maskawa Angle $\gamma$ with $B^+ \rightarrow D^{(*)+}K^{(*)-}$ Decays


(BABAR Collaboration)

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We report the measurement of the Cabibbo-Kobayashi-Maskawa CP-violating angle $\gamma$ through a Dalitz plot analysis of neutral $D$-meson decays to $K^0_S\pi^+\pi^-$ and $K^0_L K^+ K^-$ produced in the processes $B^- \rightarrow D K^+$, $B^0 \rightarrow D^* K^0$, with $D^* \rightarrow D \pi^0$, $D^0$, and $B^- \rightarrow D K^+ \pi^-$ with $K^+ \rightarrow K^0_L \pi^+$, using 468 million $B\bar{B}$ pairs collected by the BABAR detector at the PEP-II asymmetric-energy $e^+e^-$ collider at SLAC. We measure $\gamma = (68 \pm 14 \pm 4 \pm 3)^\circ$ (modulo 180°), where the first error is statistical, the second is the experimental systematic uncertainty, and the third reflects the uncertainty in the description of the neutral $D$ decay amplitudes. This result is inconsistent with $\gamma = 0$ (no direct CP violation) with a significance of 3.5 standard deviations.

The breaking of the CP symmetry in the quark sector of the electroweak interactions arises in the standard model from a single irreducible phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. This phase can be measured using a variety of methods involving B-meson decays mediated by either only tree-level or both tree- and loop-level amplitudes. The comparison of these two classes of measurements tests the CKM mechanism, thus offering a strategy to search for new physics [2].

The angle $\gamma$ of the unitarity triangle, defined as $|\arg[-V_{ub}V_{cb}^*/V_{cd}V_{tb}^*]|$, where $V_{ij}$ are elements of the CKM matrix, is particularly relevant since it is the only CP-violating parameter that can be cleanly determined using solely tree-level B-meson decays. Its precise determination constitutes an important goal of present and future experiments in flavor physics.

In $B^+ \to D K^-$ decays [3,4] the color-favored $B^+ \to D^0 K^-$ ($b \to c \bar{u}s$) and the color-suppressed $B^+ \to D^0 K^-$ ($b \to u \bar{c}s$) transitions [5] interfere when the $D^0$ and $\bar{D}^0$ decay to a common final state [6]. The two interfering amplitudes differ by a factor $r_B e^{i(\delta_\pi - \gamma)}$, where $r_B$ is the magnitude of the ratio of the amplitudes $\mathcal{A}(B^+ \to D K^-)$ and $\bar{\mathcal{A}}(B^+ \to \bar{D} K^-$), and $\delta_\pi$ is their relative strong phase. An amplitude analysis of the Dalitz plot (DP) of $D^0$ and $\bar{D}^0$ mesons decaying into the $K_S^0 \pi^+ \pi^-$ and $K_S^0 \pi^- \pi^+$ self-conjugate final states from $B^+ \to D K^-$ decays offers a unique way to access the complex amplitude ratios and thus the weak and strong phases, and $r_B$. The experimental sensitivity to $\gamma$ arises mostly from regions in the DP where Cabibbo-favored and doubly-Cabibbo-suppressed amplitudes interfere, and from regions populated by CP eigenstates; thus the uncertainty in $\gamma$ depends on $1/r_B (r_B \sim 0.1-0.2)$.

In this Letter we study the interference between color-favored and color-suppressed transitions as a function of the position in the DP of squared invariant masses $m_{s+} = m^2(K_S^0 h^-)$, $m_{s-} = m^2(K_S^0 h^+)$, where $h$ represents $\pi$ or $K$, for three related $B$ decays, $B^+ \to D K^-$, $B^+ \to D^* K^-$, and $B^+ \to D K^{*+}$ [4,7], and report the most precise single measurement of the complex amplitude ratios and evidence for direct CP violation. We use the complete data sample of 425 fb$^{-1}$ of integrated luminosity at the $\Upsilon(4S)$, corresponding to $468 \times 10^9 B\bar{B}$ pairs, and 45 fb$^{-1}$ at a center-of-mass (c.m.) energy 40 MeV below the $\Upsilon(4S)$, recorded by the BABAR experiment [8] at the PEP-II asymmetric-energy $e^+ e^-$ collider at SLAC from 1999 to 2008. This measurement updates our previous results based on a partial sample of $383 \times 10^9 B\bar{B}$ pairs, from which we reported a significance of direct CP violation ($\gamma \neq 0$) of 3.0 standard deviations, while most of the analysis details remain unchanged [9]. The Belle Collaboration using $B^+ \to D^{(*)} K^-$, $D \to K_S^0 \pi^+ \pi^-$ alone [10] has also reported $\gamma \neq 0$ with a significance of 3.5 standard deviations.

We reconstruct a total of eight signal samples, $B^+ \to D^{(*)} K^-$ and $B^+ \to D K^{*+}$, with $D \to D^0 \pi^0$, $D\gamma$, $K^+ \to K_S^0 \pi^+$, with selection criteria nearly identical to our previous analysis. The $D K^{*}$ final state, for $D \to K_S^0 K^+ K^-$, has been considered for the first time. For $K_S^0 \to \pi^+ \pi^-$ candidates, we further require the decay length (defined by the $K_S^0$ production and decay vertices) projected along the $K_S^0$ momentum to be greater than 10 times its error. This additional requirement helps to reduce to a negligible level background events from $D \to \pi^+ \pi^- h^- h^+$ decays, and from $a_1(1260)^0$ misreconstructed as $K^{*+}$. After all the selection criteria the background is completely dominated by random combinations of tracks arising from continuum events, $e^+ e^- \to q\bar{q}$ ($q = u, d, s$, or $c$). Background contributions from $D \to K^0_S K^0_S$ decays are found to be negligible. The $B^-$ candidates are characterized using the beam-energy substituted $B$ mass $m_{ES}$, the difference between the reconstructed energy of the $B^-$ candidate and the beam energy in the $e^+ e^-$ c.m. frame $\Delta E$, and a Fisher discriminant $F$ that combines four topological variables optimized to separate continuum events [9]. We retain candidates with the loose requirements $m_{ES} > 5.2$ GeV/$c^2$, $|\Delta E| < 120$ MeV, and $|F| < 1.4$, which provide signal and sideband regions while removing poorly reconstructed candidates [11]. The reconstruction efficiencies in a signal region with $m_{ES} > 5.272$ GeV/$c^2$ and $|\Delta E| < 30$ MeV are 26%, 12%, 15%, and 14%, for the $D K^+$, $D^* \bar{D} \pi^0 K^+$, $D^+ \bar{D} \gamma K^+$, and $D K^{*+}$ final states, respectively, for $D \to K^0_S \pi^+ \pi^-$ (and slightly lower for $D \to K^0_S K^+ K^-$). These values are about 30%, 40%, 30%, and 20% larger than in our previous analysis, with similar background levels, reflecting improvements in tracking and particle identification.

The $m_{ES}$, $\Delta E$, $F$, and ($s_-, s_+$) distributions for events in the signal region can be found in [11].

The $D^0 \to K^0_S h^+ h^-$ decay amplitudes $\mathcal{A}(s_-, s_+)$ are determined using the same data sample through DP analyses of $D^0$ mesons from $D^{(*)} \to D^0 \pi^+$ decays produced in $e^+ e^- \to c\bar{c}$ events [9,12]. The charge of the low momentum $\pi^+$ from the $D^*$ decay identifies the flavor of the $D$ meson. The signal purities of the samples are 98.5% and 99.2%, with about 541 000 and 80 000 candidates, for the $K_S^0 \pi^+ \pi^-$ and $K_S^0 K^+ K^-$, respectively. The dynamical properties of the $P$- and $D$-wave amplitudes are parametrized through intermediate resonances with mass-dependent relativistic Breit-Wigner (BW) or Gounaris-Sakurai propagators, Blatt-Weisskopf centrifugal barrier factors, and Zemach tensors for the angular distributions [13]. The $\pi \pi$ S-wave dynamics is described through a $K$-matrix formalism with the $P$-vector approximation and 5 poles [9,14]. For the $K \pi$ S-wave we include a BW for the $K_S^0(1430)^+$ state with a coherent nonresonant contribution parametrized by a scattering length and effective range similar to those used to describe $\bar{K} \pi$ scattering data [15].

For the $KK$ S-wave, a coupled-channel BW is used for the $a_0(980)$ with single BWs for $f_0(1370)$ and $a_0(1450)$ states. Overall, the amplitude models reproduce well the DP distributions [12]. Monte Carlo (MC) studies show that a significant contribution to the discrepancies arise from imperfections modeling the efficiency variations at the...
identification components, along with the resolution across the DP [9]. For each signal sample, the function of CP results. The probability density functions (PDFs) introduced as a consequence of the K⁺ natural width [9,16,17]. Assuming no CP violation and neglecting D⁰ − D̅⁰ mixing in D⁰ → K⁰h⁺h⁻ decays [12,18,19], the relation \( \bar{\mathcal{A}}(s_-, s_+) = \mathcal{A}(s_-, s_+) \) holds, where \( \bar{\mathcal{A}} \) is the \( \bar{D} \) decay amplitude. The \( B^- \rightarrow D⁻(\pi^+)K^- \) and \( B^- \rightarrow D⁻(\pi^+)K^- \) replacing \( z_{s}^{(s)} \) and \( r_{s}^{(s)} \) by \( z_{s}^{(s)} \) and \( r_{s}^{(s)} \), respectively) signal decay rates are then

\[
\Gamma_{\pi}^{(s)}(s_-, s_+) \propto |\mathcal{A}_{\pi}^{(s)}|² + |r_{B}^{(s)}|² |\mathcal{A}_{\pi}^{(s)}|² + 2\lambda z_{s}^{(s)} |\mathcal{A}_{\pi}^{(s)}|²,
\]

with \( \mathcal{A}_{\pi}^{(s)} = \mathcal{A}(s_-, s_+) \), and \( \lambda = +1 \) except for \( B^- \rightarrow D²[D\pi^-]K^- \) where \( \lambda = -1 \) [20]. We apply corrections for efficiency variations and neglect the invariant mass resolution across the DP [9]. For each signal sample, the following background components are considered: continuum events, \( B^- \rightarrow D⁻(\pi^+)K^- \) where the pion is mis-identified as a kaon [only for \( B^- \rightarrow D⁻(\pi^+)K^- \) samples], and \( Y(4S) \rightarrow BB \) [other than \( B^- \rightarrow D⁻(\pi^+)K^- \) decays. The reference CP fit requires events to satisfy |ΔE| < 30 MeV, but alternative fits are performed varying the requirements on the \( m_{ES} \), \( m_{ES} \), and \( \mathcal{F} \) variables (e.g. \( m_{ES} > 5.272 \text{ GeV}/c² \) or \( \mathcal{F} > -0.1 \)) to study the stability of the results. The probability density functions (PDFs) introduced to describe the signal, continuum, and \( K/\pi \) misidentification components, along with the \( K/\pi \) misidentification yields, are determined using events from signal and \( B^- \rightarrow D⁻(\pi^+)K^- \), \( D_{0}\bar{\Lambda}(1260)\bar{\pi}^0 \) control samples. The PDFs for \( BB \) background events are obtained from large MC samples with full detector simulations [9].

The CP fit yields 896 ± 35 (154 ± 14), 255 ± 21 (56 ± 11), 193 ± 19 (30 ± 7), and 163 ± 18 (28 ± 6) signal \( DK^- \), \( D⁻[D\pi^-]K^- \), \( D⁻[D\gamma]K^- \), and \( D⁻[\pi^+\pi^-]K^- \) events, respectively, for the \( K⁰\pi^+\pi^- \), \( K⁰K^-\bar{K}^- \) final state. The results for the CP-violating parameters \( z_{s}^{(s)} \) and \( z_{s}^{(s)} \) are summarized in Table I. Figure 1 shows the 39.3% and 86.5% two-dimensional confidence-level (C.L.) contours in the \( z_{s}^{(s)} \) and \( z_{s}^{(s)} \) planes, corresponding to one- and two-standard deviation regions, including statistical errors only. The distance between the \( z_- \) and \( z_+ \) central values (and similarly for \( z_- \) and \( z_+ \)) is equal to \( 2\bar{r}_{B} \), and the angle defined by the lines connecting the central values with the origin is \( 2\gamma \), and thus is a measurement of direct CP violation. Fitting separately the data for \( K⁰\pi^+\pi^- \) and \( K⁰K^-\bar{K}^- \) final states we find consistent results for all the CP-violating parameters [11].

Experimental systematic errors [9,11] originate from uncertainties in the description of the efficiency variations across the DP, the modeling of the DP distributions for background events containing misreconstructed \( D \) mesons, the fractions of continuum, and \( BB \) background events containing a real \( D \) meson with either a negatively or positively charged kaon (or \( K^* \)), and from residual direct CP violation in the \( B^- \rightarrow D^0\pi^\mp \pi^- \) and \( BB \) background components. We also account for statistical and systematic uncertainties in the \( m_{ES} \), \( \mathcal{E} \), and \( \mathcal{F} \) PDF shapes for signal and background components, and the \( K/\pi \) misidentification yields. These uncertainties account for effects that arise from the dependence of the \( m_{ES} \) endpoint, the peaking contributions to the small \( BB \) background, and the \( e^+e^- \) c.m. frame. Smaller systematic uncertainties originate from the DP resolution, wrongly reconstructed signal events with a real \( D \) and a kaon (or \( K^* \)) from the other \( B \) meson decay, the selection of \( B \) candidates sharing tracks with other candidates, and numerical precision in the evaluation of the PDF integrals. We also account for residual cross feed of \( B^- \rightarrow D^0[D\pi^0]K^- \) events into the \( B^- \rightarrow D^0[D\gamma]K^- \) events (about 5%), and the estimated uncertainty on the hadronic parameter \( \kappa = 0.9 \pm 0.1 \) in the \( B^- \rightarrow D^0\pi^\mp \) sample [9,21].

Assumptions in the \( D^0 \) decay amplitude models are also a source of systematic uncertainty [9,11,12]. We use alternative \( \mathcal{A}(s_-, s_+) \) models where the BW parameters are varied according to their uncertainties or within the ranges allowed by measurements from other experiments, the reference \( K \)-matrix solution [9] is replaced by other solutions [14], and the standard parametrizations are substituted by other related choices. These include replacing the

| TABLE I. CP-violating complex parameters \( z_{s}^{(s)} = x_{s}^{(s)} + iy_{s}^{(s)} \) and \( z_{s}^{(s)} = x_{s}^{(s)} + iy_{s}^{(s)} \) as obtained from the CP fit. The first error is statistical, the second is the experimental systematic uncertainty, and the third is the systematic uncertainty associated with the \( D^0 \) decay amplitude models. |
|----------------|----------------|----------------|
|                | Real Part (%)  | Imaginary Part (%) |
| \( z_- \)      | 6.0 ± 3.9      | 0.7 ± 0.6       |
| \( z_+ \)      | -10.3 ± 3.7    | 0.6 ± 0.7       |
| \( z_-^* \)    | -10.4 ± 5.1    | 1.9 ± 0.2       |
| \( z_+^* \)    | 14.7 ± 5.3     | 1.7 ± 0.3       |
| \( z_- \)      | 7.5 ± 9.6      | 2.9 ± 0.7       |
| \( z_+ \)      | -15.1 ± 8.3    | 2.9 ± 0.6       |
Gounaris-Sakurai and $K\pi$ S-wave parametrizations by BW line shapes, removing the mass dependence in the $P$ vector [22], changes in form factors such as changes in the Blatt-Weisskopf radius, and adopting a helicity formalism [13] to describe the angular dependence. Other models are built by removing or adding resonances with small or negligible fractions. We find that the overall amplitude model uncertainty on the $CP$ parameters are dominated by alternative models built to account for experimental systematic effects in the determination of $\mathcal{A}(s_-, s_+)$ using tagged $D$ mesons [12]. The statistical errors and variations in the $\mathcal{A}(s_-, s_+)$ model parameters with and without $D^0 - \bar{D}^0$ mixing are also propagated to $z^{(a)}$ and $z^{(b)}$.

Experimental and amplitude model systematic uncertainties [11] have been reduced with respect to our previous measurement [9] as consequence of the use of larger data and MC samples, and the smaller experimental systematic contributions to the model uncertainty resulting from the improvements in the analysis of tagged $D$ mesons [12].

A frequentist construction of one-dimensional confidence intervals of the physically relevant parameters $p \equiv (\gamma, r_B, r_B^{'}, \kappa r_s, \delta_B, \delta_B^{'}, \delta_s)$ based on the vector of measurements $z = (z, z^{'}, z^{(a)}, z^{(b)}, z^{(c)})$ and their correlations [11] has been adopted [9]. The procedure takes into account unphysical regions which may arise since we allow $B^-$ and $B^+$ events to have different $f^{(*)}$, $r_{\pi^\pm}$ in the $z$ measurements. Figure 2 shows $1 - C.L.$ as a function of $\gamma$ for each of the three $B$ decay channels separately and their combination. Similar scans for $f^{(*)}$, $r_{\pi^\pm}$, $\delta_B$, and $\delta_s$ can be found in [11]. The method has a single ambiguity in the weak and strong phases. The results for all the $p$ parameters are listed in Table II. The significances of direct $CP$ violation ($\gamma \neq 0$) are 1 $C.L. = 6.8 \times 10^{-3}$, $5.4 \times 10^{-3}$, $6.3 \times 10^{-2}$, and $4.6 \times 10^{-4}$, which correspond to $2.7, 2.8, 1.9$, and $3.5$ standard deviations, for $B^+ \rightarrow DK^+$, $B^- \rightarrow D^0K^+$, $B^- \rightarrow DK^{*+}$, and their combination, respectively.

TABLE II. The 68.3% and 95.4% one-dimensional C.L. regions, equivalent to one- and two-standard deviation intervals, for $\gamma, \delta_B^{(*)}, \delta_s, f^{(*)}$, and $\kappa r_s$, including all sources of uncertainty. The values inside $\{\}$ brackets indicate the symmetric error contributions to the total error coming from experimental and amplitude model systematic uncertainties.

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<th>68.3% C.L.</th>
<th>95.4% C.L.</th>
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<td>$\gamma$ (deg)</td>
<td>$68^{+15}_{-14} {4, 3}$</td>
<td>$39, 98$</td>
</tr>
<tr>
<td>$r_B$ (%)</td>
<td>$9.6 \pm 2.9 {0.5, 0.4}$</td>
<td>$3.7, 15.5$</td>
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<tr>
<td>$r_B^{(*)}$ (deg)</td>
<td>$13.3^{+9}_{-13} {1.3, 0.3}$</td>
<td>$4.9, 21.5$</td>
</tr>
<tr>
<td>$\kappa r_s$ (%)</td>
<td>$14.9^{+6}_{-5} {2.6, 0.6}$</td>
<td>&lt;28.0</td>
</tr>
<tr>
<td>$\delta_B^{(*)}$</td>
<td>$119_{-19}^{+19} {3, 3}$</td>
<td>$75, 157$</td>
</tr>
<tr>
<td>$\delta_s^{(*)}$</td>
<td>$-82 \pm 21 {5, 3}$</td>
<td>$-124, -38$</td>
</tr>
<tr>
<td>$\delta_t^{(*)}$</td>
<td>$111 \pm 32 {11, 3}$</td>
<td>$42, 178$</td>
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We have presented a measurement of the $b \to u$ to $b \to c$ complex amplitude ratios in the processes $B^+ \to D^{(*)}K^+$ and $B^+ \to DK^{+*}$, using a combined DP analysis of $D \to K_S^0 \pi^+ \pi^-$ and $D \to K_S^0 K^+ K^-$ decays. The results have improved precision and are consistent with our previous measured values [9] and with those reported by the Belle Collaboration with $D \to K_S^0 \pi^+ \pi^-$ alone [10], and with determinations based on other $D$ meson final states [21,23,24]. From our measurement we determine $\gamma = (68 \pm 14 \pm 4 \pm 3)^\circ$ (modulo 180$^\circ$), exclude the no direct $CP$-violation hypothesis (i.e., $\gamma = 0$) with a C.L. equivalent to 3.5 standard deviations, and derive the most precise single determinations of the magnitude ratios $r_B^{(*)}$ and $\kappa r_s$.

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[4] The symbol $D (D^*)$ indicates either a $D^0 (D^{*0})$ or a $\bar{D}^0 (\bar{D}^{*0})$ meson.
[5] Reference to the charge-conjugate state is implied here and throughout the text unless otherwise specified.
[7] $K^{*+}$, $D^{*+}$, and $D^{*0}$ refer to $K^{*}(892)^+$, $D^{*}(1050)^+$, and $D^{*0}(2070)^0$, respectively.