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Measurement of the CKM-angle γ at *BABAR*

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We present the results of the measurements employed by the *BABAR* Collaboration, to determine the value of the Cabibbo-Kobayashi-Maskawa (CKM) CP -violating phase γ ($\equiv \arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$). These measurements are based on the studies performed with the charged B-decays $B^- \rightarrow \tilde{D}^0 K^-$, $B^- \rightarrow \tilde{D}^{*0} K^-$, and $B^- \rightarrow \tilde{D}^0 K^{*-}$, where \tilde{D}^0 indicates either a D^0 or a \bar{D}^0 meson. A sample of about 230 million $B\bar{B}$ pairs collected by the *BABAR* detector [1], at the PEP-II asymmetric-energy e^+e^- collider at SLAC, is used.

Three methods are exploited [2, 3, 4], where the \tilde{D}^0 decays either to a CP -eigenstate (GLW), or to a Cabibbo-suppressed flavor decay ("wrong sign", ADS), or to the $K_S^0 \pi^- \pi^+$ final state, for which a Dalitz analysis has to be performed ($GGSZ$). To extract γ , those 3 methods are all based on the fact that a B^- meson can decay into a color-allowed $D^{(*)0} K^- / K^{*-}$ (color-suppressed $\bar{D}^{(*)0} K^- / K^{*-}$) final state via $b \rightarrow c\bar{u}s$ ($b \rightarrow u\bar{c}s$) transitions. The amplitude $\mathcal{A}("V_{cb}")$ of the $b \rightarrow c\bar{u}s$ transition is proportional to λ^3 and the amplitude $A("V_{ub}")$ of the $b \rightarrow u\bar{c}s$ transition to $\lambda^3 \sqrt{\bar{\eta}^2 + \bar{\rho}^2} e^{i(\delta_{B^-} - \gamma)}$. The second amplitude therefore carries both the EW γ CP -phase and the relative strong phase of those 2 transitions. As the total measured amplitude for $B^- \rightarrow \tilde{D}^0 K^-$, $B^- \rightarrow \tilde{D}^{*0} K^-$, and $B^- \rightarrow \tilde{D}^0 K^{*-}$ decays is the sum of the 2 amplitudes $\mathcal{A}("V_{cb}")$ and $\mathcal{A}("V_{ub}")$, the 2 amplitudes interfere when the D^0 and \bar{D}^0 decay into the same final state. This interference can lead to different B^+ and B^- decay rates (direct CP -violation).

The various methods are "theoretically clean" because the main contributions to the amplitudes come from tree-level transitions. In addition to the CKM parameters and to the strong phase, $\mathcal{A}("V_{ub}")$ is significantly reduced with respect to $\mathcal{A}("V_{cb}")$ by the color suppression phenomenon. One usually defines the parameter $r_B \equiv |\mathcal{A}("V_{ub"}) / \mathcal{A}("V_{cb"})|$ that determines the size of the direct CP asymmetry. It is the critical parameter for these analyzes. Its value is predicted [5] to lie in the range 0.1 – 0.3. The smaller r_B is, the smaller is the experimental sensitivity to γ .

A combination of the various constraints obtained with these methods is performed. It is based on a frequentist approach [6] where the world average of the GLW and ADS methods is combined with the result of the *BABAR* Dalitz analysis [7]. It constrains the angle γ to have a value equal to $[51_{-18}^{+23}]^\circ$ and consistent with the overall indirect prediction obtained for the standard model CKM triangle fit: $[57_{-13}^{+7}]^\circ$. The *BABAR* Dalitz analysis alone measures $\gamma = [67 \pm 28(stat.) \pm 13(syst.) \pm 11(Dalitz\ model)]^\circ$. Incidentally, It should be emphasized that these somewhat precise measurements were considered as unreachable at B-factories a few years ago.

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1. Introduction to the various physical quantities

The 2 parameters " r_B " and " δ_B " depend on the studied decay: $B^- \rightarrow \tilde{D}^0 K^-$ (δ_B and r_B) or $B^- \rightarrow \tilde{D}^{*0} K^-$ (δ_B^* and r_B^*) or $B^- \rightarrow \tilde{D}^0 K^{*-}$ (δ_{sB} and r_{sB}). The CKM-angle γ , and the parameters " r_B ", and " δ_B " can be measured experimentally through the 2 observable quantities (Asymmetry and Ratio of Branching Ratios):

$$\mathbf{A} \equiv \frac{\Gamma(B^- \rightarrow \tilde{D}^{(*)0} K^{(*)-}) - \Gamma(B^+ \rightarrow \tilde{D}^{(*)0} K^{(*)+})}{\Gamma(B^- \rightarrow \tilde{D}^{(*)0} K^{(*)-}) + \Gamma(B^+ \rightarrow \tilde{D}^{(*)0} K^{(*)+})}, \quad (1.1)$$

$$\mathbf{R} \equiv \frac{\Gamma(B^- \rightarrow \tilde{D}^{(*)0} K^{(*)-}) + \Gamma(B^+ \rightarrow \tilde{D}^{(*)0} K^{(*)+})}{\Gamma(B^- \rightarrow D^{(*)0} K^{(*)-}) + \Gamma(B^+ \rightarrow \bar{D}^{(*)0} K^{(*)+})}. \quad (1.2)$$

Both *BABAR* [8] and Belle [9] Collaborations have produced results for these three methods at the time of spring 2005. We essentially present here new results for the decay $B^- \rightarrow \tilde{D}^0 K^{*-}$ ($K^*(892)^-$ decays where $K^{*-} \rightarrow K_S^0 \pi^-$). The analyzes are described in details in [10, 11, 7].

2. The *GLW* analysis [2, 8, 10]

The \tilde{D}^0 is reconstructed in various *CP*-eigenstates decay channels: $K^+ K^-$, $\pi^+ \pi^-$ (*CP*+ eigenstates); and $K_S^0 \pi^0$, $K_S^0 \phi$, $K_S^0 \omega$ (*CP*- eigenstates). The \mathbf{R}_{CP} is normalized to the branching ratios as obtained from 3 flavor state decays: $D^0 \rightarrow K^- \pi^+$, $K^- \pi^+ \pi^0$, and $K^- \pi^+ \pi^+ \pi^-$. One has 4 observable quantities, for 3 unknown (γ , r_B , and δ_B): $\mathbf{R}_{CP\pm} = 1 \pm 2r_B \cos \delta \cos \gamma + r_B^2$ and $\mathbf{A}_{CP\pm} = \frac{\pm 2r_B \sin \delta \sin \gamma}{\mathbf{R}_{CP\pm}}$. Only 3 are independent, as: $\mathbf{R}_{CP-} \mathbf{A}_{CP-} = -\mathbf{R}_{CP+} \mathbf{A}_{CP+}$. In principle with infinite statistics this method is very clean to determine γ (with 8 fold-ambiguities). But the small *CP*-asymmetry (small $r_B \simeq 0.1 - 0.3$) and the small secondary branching ratios to produce the D^0 *CP*-eigenstates, make this method difficult with the present B-factories dataset.

For the $B^- \rightarrow \tilde{D}^0 K^{*-}$ decay [10], we measure: $\mathbf{A}_{CP+} = -0.08 \pm 0.19 \pm 0.08$, $\mathbf{R}_{CP+} = -0.26 \pm 0.40 \pm 0.12$, $\mathbf{A}_{CP-} = 1.96 \pm 0.40 \pm 0.11$, and $\mathbf{R}_{CP-} = 0.65 \pm 0.26 \pm 0.08$, where the first uncertainty is statistical and the second systematic. The (peaking)-background is estimated from the m_{ES} and m_{D^0} side-bands. The *CP*+ pollution for *CP*- eigenstate from decays $K_S^0 [K^+ K^-]_{\text{non } \phi}$ and $K_S^0 [\pi^+ \pi^- \pi^0]_{\text{non } \omega}$ is estimated using data. Finally, we take into account in the systematic uncertainties the possible strong phases as generated by probable $K\pi$ S-waves in the $K^{*-} \rightarrow K_S^0 \pi^-$ decays. From $\mathbf{R}_{CP\pm}$ we also derive $rs_B^2 = 0.30 \pm 0.25$. When one defines the so-called *Cartesian coordinates*: $xs^\pm \equiv rs_B \cos(\delta_s \pm \gamma)$, we find: $xs^+ = 0.32 \pm 0.18$ (*stat.*) ± 0.07 (*syst.*), $xs^- = 0.33 \pm 0.16$ (*stat.*) ± 0.06 (*syst.*). At the present time, the measured values of \mathbf{A}_{CP} (\mathbf{R}_{CP}) are not precise enough to differ significantly from 0 (1) so that a strong constraint on γ can be obtained from the *GLW* method alone.

3. The *ADS* analysis [3, 8, 11]

The D^0 meson as generated from the $b \rightarrow c\bar{u}s$ transition is required to decay to the doubly Cabibbo-suppressed $K^+ \pi^-$ mode ("wrong sign"), while the \bar{D}^0 meson, from the interfering $b \rightarrow u\bar{c}s$ transition, decays to Cabibbo-favored final state $K^+ \pi^-$. The overall branching ratio for a final state $B^- \rightarrow [K^+ \pi^-]_{\tilde{D}^0} K^{(*)-}$ is expected to be small ($\sim 10^{-6}$), but the 2 interfering diagrams

are now of the same order of magnitude. The challenge in this method is therefore to detect B candidate in this final state with 2-opposite charge kaons. The total amplitude is complicated by an additional unknown relative strong phase δ_D in the $D^0\text{-}\bar{D}^0 \rightarrow [K^+\pi^-]$ system, while the ratio of their respective amplitude r_D is precisely measured at the level of 6 % [12]. It can be written as $A([K^+\pi^-]_{\bar{D}^0}K^{(*)-}) \propto r_B e^{i(\delta_B-\gamma)} + r_D e^{-i\delta_D}$. Using the $B^- \rightarrow [K^-\pi^+]K^{(*)-}$ modes as normalisation for \mathbf{R}_{ADS} , one can write the equations for the 2 experimental observable quantities: $\mathbf{R}_{ADS} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos(\gamma)$ and $\mathbf{A}_{ADS} = \frac{2 r_B r_D \sin(\delta_B + \delta_D) \sin(\gamma)}{\mathbf{R}_{ADS}}$. Where \mathbf{R}_{ADS} is clearly highly sensitive to r_B^2 .

For the $B^- \rightarrow \tilde{D}^0 K^-$ and $B^- \rightarrow \tilde{D}^{*0} K^-$ channels [8], no significant ADS signal has been measured yet. At 90 % of confidence level, we set the upper limits $r_B < 0.23$ and $r_B^{*2} < (0.16)^2$, respectively for the 2 decay modes. For the $B^- \rightarrow \tilde{D}^0 K^{*-}$ decay [11], we have also not seen any significant ADS signal, we measure $\mathbf{R}_{ADS} = 0.046 \pm 0.031 \pm 0.008$, $\mathbf{A}_{ADS} = -0.22 \pm 0.61 \pm 0.17$, where the first uncertainty is statistical and the second systematic. As part of the systematic uncertainties, we consider effect of the possible strong phases as generated by probable $K\pi$ S-waves in the $K^{*-} \rightarrow K_S^0 \pi^-$ decays. It is the dominant contribution.

Using a frequentist approach [6], and combining both the GLW and ADS methods for the $B^- \rightarrow \tilde{D}^0 K^{*-}$ channel [11], we determine $rs_B = 0.28_{-0.10}^{+0.06}$, and we can exclude at the two-standard deviation level the interval $75^\circ < \gamma < 105^\circ$.

4. The $K_S^0 \pi^- \pi^+$ Dalitz analysis [4, 8, 7]

Among the \tilde{D}^0 decay modes studied so far the $K_S^0 \pi^- \pi^+$ channel is the one with the highest sensitivity to γ because of the best overall combination of branching ratio magnitude, $D^0 - \bar{D}^0$ interference and background level. This mode offers a reasonably high branching ratio (10^{-5} , including secondary decays) and a clean experimental signature (only charged tracks in the final state). The decay mode $K_S^0 \pi^- \pi^+$ can be accessed through many intermediate states: "wrong sign" or "right" K^* resonances, $K_S^0 \rho^0$ CP - eigenstate, ... Therefore, an analysis of the the amplitude of the \tilde{D}^0 decay over the $m^2(K_S^0 \pi^-)$ vs. $m^2(K_S^0 \pi^+)$ (m_-^2 vs. m_+^2) Dalitz plane structure is sensitive to the same kind of observable as for both the GLW and ADS methods. The sensitivity to γ varies strongly over the Dalitz plane. The contribution from the $b \rightarrow u\bar{c}s$ transition in the $B^- \rightarrow D^{(*)0} K^- / K^{*-}$ ($B^+ \rightarrow \bar{D}^{(*)0} K^+ / K^{*+}$) decay can significantly be amplified by the amplitude \mathcal{A}_{D^+} (\mathcal{A}_{D^-}) of the $\bar{D}^0 \rightarrow K_S^0 \pi^- \pi^+$ ($D^0 \rightarrow K_S^0 \pi^+ \pi^-$) decay ($\mathcal{A}_{D^\mp} \equiv \mathcal{A}_D(m_\mp^2, m_\pm^2)$). Assuming no CP asymmetry in D decays, the decay rate of the chain $B^- \rightarrow D^{(*)0} K^- / K^{*-}$ ($B^+ \rightarrow \bar{D}^{(*)0} K^+ / K^{*+}$), and $\tilde{D}^0 \rightarrow K_S^0 \pi^- \pi^+$, can be written as: $\Gamma_\mp(m_-^2, m_+^2) \propto |\mathcal{A}_{D^\mp}|^2 + r_B^2 |\mathcal{A}_{D^\pm}|^2 + 2 \{x_\mp \text{Re}[\mathcal{A}_{D^\mp} \mathcal{A}_{D^\pm}^*] + y_\mp \text{Im}[\mathcal{A}_{D^\mp} \mathcal{A}_{D^\pm}^*]\}$.

We have introduced the *Cartesian coordinates*: $\{x_\mp, y_\mp\} = \{\text{Re}, \text{Im}\}[r_B e^{i(\delta_B \mp \gamma)}]$, for which the constraint $r_B^2 = x_\mp^2 + y_\mp^2$ holds. These are natural parameters to describe the amplitude of the decay. A simultaneous fit both to the B^\pm decays and $\tilde{D}^0 \rightarrow K_S^0 \pi^- \pi^+$ decays is then performed to extract 12 parameters: $\{x_-, y_-\}$ from $B^- \rightarrow \tilde{D}^0 K^-$, $\{x_+, y_+\}$ from $B^- \rightarrow \tilde{D}^{*0} K^-$, and $\{x_s, y_s\}$ from $B^- \rightarrow \tilde{D}^0 K^{*-}$. In the last case, we deal with $(K_S^0 \pi^\mp)_{\text{non-}K^*}$ contribution, by defining an effective dilution parameter κ as $x_{s^\mp}^2 + y_{s^\mp}^2 = \kappa^2 r_B^2$, with $0 \leq \kappa \leq 1$.

Since the measurement of γ arises from the interference term in $\Gamma_\mp(m_-^2, m_+^2)$, the uncertainty in the knowledge of the complex form of \mathcal{A}_D can lead to a systematic uncertainty. Two different models describing the $D^0 \rightarrow K_S^0 \pi^- \pi^+$ decay have been used in the recent $BABAR$ analysis [7].

The first model (also referred to as Breit-Wigner model) is the same as used for our previously reported measurement of γ on $B^- \rightarrow \tilde{D}^{(*)0} K^-, \tilde{D}^0 \rightarrow K_s^0 \pi^- \pi^+$ decays [8], and expresses \mathcal{A}_D as a sum of two-body decay-matrix elements and a non-resonant contribution. In the second model (hereafter referred to as the $\pi\pi$ S-wave K-matrix model) the treatment of the $\pi\pi$ S-wave states in $D^0 \rightarrow K_s^0 \pi^- \pi^+$ uses a K-matrix formalism to account for the non-trivial dynamics due to the presence of broad and overlapping resonances. The two models have been obtained using a high statistics flavor tagged D^0 sample ($D^{*+} \rightarrow D^0 \pi_s^+$) selected from $e^+e^- \rightarrow c\bar{c}$ events recorded by BABAR.

At the end of the analysis, the 7 parameters: γ , δ_B , δ_B^* , δ_{sB} , r_B , r_B^* , and $\kappa.r_{sB}$, are extracted from the 12 *Cartesian coordinates* using a frequentist approach that defines a 7 – *D* Neyman Confidence Region. The values for all these parameters can be found in the documents [8] and [7]. But it should be noticed that the values of r_B and r_B^* stand in the range 0 – 0.35 (2-standard deviation interval) while $\kappa.r_{sB}$ is presently less constrained (< 0.75).

The overall value for the *EW CP* phase is: $\gamma = [67 \pm 28(stat.) \pm 13(syst.) \pm 11(Dalitz\ model)]^\circ$. Where it can be noticed that the uncertainty coming from the employed *Dalitz model* would limit the measurement at infinite statistic. Though so far we have used the "Breit-Wigner model" to perform the fit, it has been checked that the relative systematic uncertainty of that measurement with respect to a fit to the "the $\pi\pi$ S-wave K-matrix model" is 3° (incorporated in the above result). This indicates that the Dalitz model uncertainty could eventually be strongly reduced in a future analysis.

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