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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 ($\equiv \arg\left[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}\right]$). These measurements are based on the studies performed with the charged B-decays $B^- \to \tilde{D}^0 K^-$, $B^- \to \tilde{D}^{*0} K^-$, and $B^- \to \tilde{D}^0 K^{*-}$, 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 $K^0_S\pi^-\pi^+$ 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 $b \to c\bar{u}s$ ($b \to u\bar{c}s$) transitions. The amplitude $\mathscr{A}$(“V_{cb}”) of the $b \to c\bar{u}s$ transition is proportional to λ^3 and the amplitude A(“V_{ub}”) of the $b \to u\bar{c}s$ 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 $B^- \to \tilde{D}^0 K^-$, $B^- \to \tilde{D}^{*0} K^-$, and $B^- \to \tilde{D}^0 K^{*-}$ decays is the sum of the 2 amplitudes $\mathscr{A}$(“V_{cb}”) and $\mathscr{A}$(“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, $\mathscr{A}$(“V_{ub}”) is significantly reduced with respect to $\mathscr{A}$(“V_{cb}”) by the color suppression phenomenon. One usually defines the parameter $r_B \equiv |\mathscr{A}(\text{“}V_{ub}\text{”})/\mathscr{A}(\text{“}V_{cb}\text{”})|$ 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 $[51^{+23}_{-18}]^\circ$ and consistent with the overall indirect prediction obtained for the standard model CKM triangle fit: $[57^{+7}_{-13}]^\circ$. 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: $B^- \to \tilde{D}^0 K^-$ (δ_B and r_B) or $B^- \to \tilde{D}^{*0} K^-$ (δ^*_B and r^*_B) or $B^- \to \tilde{D}^0 K^{*-}$ (δs_B and rs_B). 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):

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

$$\mathbf{R} \equiv \frac{\Gamma(B^- \to \tilde{D}^{(*)0} K^{(*)-}) + \Gamma(B^+ \to \tilde{D}^{(*)0} K^{(*)+})}{\Gamma(B^- \to D^{(*)0} K^{(*)-}) + \Gamma(B^+ \to \overline{D}^{(*)0} K^{(*)+})}. \tag{1.2}$$

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 $B^- \to \tilde{D}^0 K^{*-}$ ($K^*(892)^-$ decays where $K^{*-} \to K^0_S \pi^-$). 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 $K^0_S\pi^0$, $K^0_S\phi$, $K^0_S\omega$ ($CP-$ eigenstates). The $\mathbf{R}_{CP}$ is normalized to the branching ratios as obtained from 3 flavor state decays: $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, 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 $B^- \to \tilde{D}^0 K^{*-}$ 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 $m_{\rm ES}$ and mD^0 side-bands. The $CP+$ pollution for $CP-$ eigenstate from decays $K^0_S[K^+K^-]_{\text{non }\phi}$ and $K^0_S[\pi^+\pi^-\pi^0]_{\text{non }\omega}$ 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 $K^{*-} \to K^0_S\pi^-$ 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: $xs^+ = 0.32 \pm 0.18\ (stat.) \pm 0.07\ (syst.)$, $xs^- = 0.33 \pm 0.16\ (stat.) \pm 0.06\ (syst.)$. 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 $b \to c\bar{u}s$ transition is required to decay to the doubly Cabibbo-suppressed $K^+\pi^-$ mode ("wrong sign"), while the $\bar{D}^0$ meson, from the interfering $b \to u\bar{c}s$ transition, decays to Cabibbo-favored final state $K^+\pi^-$. The overall branching ratio for a final state $B^- \to [K^+\pi^-]_{\tilde{D}^0} K^{(*)-}$ 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-$\bar{D}^0 \to [K^+\pi^-]$ system, while the ratio of their respective amplitude r_D is precisely measured at the level of 6 % [12]. It can be written as $A([K^+\pi^-]_{\tilde{D}^0}K^{(*)-}) \propto \mathrm{r}_B e^{i(\delta_B-\gamma)} + \mathrm{r}_D e^{-i\delta_D}$. Using the $B^- \to [K^-\pi^+]K^{(*)-}$ modes as normalisation for $\mathbf{R}_{ADS}$, one can write the equations for the 2 experimental observable quantities: $\mathbf{R}_{ADS} = r_B^2 + r_D^2 + 2r_Br_D\cos(\delta_B+\delta_D)\cos(\gamma)$ and $\mathbf{A}_{ADS} = \frac{2\, r_Br_D\sin(\delta_B+\delta_D)\sin(\gamma)}{\mathbf{R}_{ADS}}$. Where $\mathbf{R}_{ADS}$ is clearly highly sensitive to r_B^2.

For the $B^- \to \tilde{D}^0K^-$ and $B^- \to \tilde{D}^{*0}K^-$ channels [8], no significant *ADS* signal has been measured yet. At 90 % of confidence level, we set the upper limits $\mathrm{r}_B < 0.23$ and $\mathrm{r}^{*2}_B < (0.16)^2$, respectively for the 2 decay modes. For the $B^- \to \tilde{D}^0K^{*-}$ 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 $K^{*-} \to K^0_S\pi^-$ decays. It is the dominant contribution.

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

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

Among the $\tilde{D}^0$ decay modes studied so far the $K^0_S\pi^-\pi^+$ 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 $K^0_S\pi^-\pi^+$ can be accessed through many intermediate states: "wrong sign" or "right" K^* resonances, $K^0_S\rho^0$ *CP*$-$ eigenstate, ... Therefore, an analysis of the the amplitude of the $\tilde{D}^0$ decay over the $m^2(K^0_S\pi^-)$ *vs.* $m^2(K^0_S\pi^+)$ (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 $b \to u\bar{c}s$ transition in the $B^- \to D^{(*)0}K^-/K^{*-}$ ($B^+ \to \bar{D}^{(*)0}K^+/K^{*+}$) decay can significantly be amplified by the amplitude $\mathscr{A}_{D+}$ ($\mathscr{A}_{D-}$) of the $\bar{D}^0 \to K^0_S\pi^-\pi^+$ ($D^0 \to K^0_S\pi^+\pi^-$) decay ($\mathscr{A}_{D\mp} \equiv \mathscr{A}_D(m^2_\mp, m^2_\pm)$). Assuming no *CP* asymmetry in D decays, the decay rate of the chain $B^- \to D^{(*)0}K^-/K^{*-}$ ($B^+ \to \bar{D}^{(*)0}K^+/K^{*+}$), and $\tilde{D}^0 \to K^0_S\pi^-\pi^+$, can be written as: $\Gamma_\mp(m^2_-, m^2_+) \propto |\mathscr{A}_{D\mp}|^2 + r_B^2|\mathscr{A}_{D\pm}|^2 + 2\left\{x_\mp \,\mathrm{Re}[\mathscr{A}_{D\mp}\mathscr{A}^*_{D\pm}] + y_\mp \,\mathrm{Im}[\mathscr{A}_{D\mp}\mathscr{A}^*_{D\pm}]\right\}$.

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

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 $\mathscr{A}_D$ can lead to a systematic uncertainty. Two different models describing the $D^0 \to K^0_S\pi^-\pi^+$ 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 $B^- \to \tilde{D}^{(*)0}K^-$, $\tilde{D}^0 \to K_S^0\pi^-\pi^+$ decays [8], and expresses $\mathscr{A}_D$ 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 $D^0 \to K_S^0\pi^-\pi^+$ 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 ($D^{*+} \to D^0\pi_s^+$) selected from $e^+e^- \to c\overline{c}$ events recorded by *BABAR*.

At the end of the analysis, the 7 parameters: γ, δ_B, δ_B^*, δs_B, r_B, r_B^*, and $\kappa.rs_B$, 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 $\kappa.rs_B$ 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.

References

[1] *BABAR* Collaboration, B. Aubert *et al.*, Nucl. Instrum. Methods **A479**, 1-116 (2002).

[2] M. Gronau and D. London, Phys. Lett. B **253**, 483 (1991); M. Gronau and D. Wyler, Phys. Lett. B **265**, 172 (1991);

[3] D. Atwood, I. Dunietz and A. Soni, Phys. Rev. Lett. **78**, 3257 (1997).

[4] A. Giri, Yu. Grossman, A. Soffer and J. Zupan, Phys. Rev. D **68**, 054018 (2003).

[5] M. Gronau, Phys. Lett. **B557**, 198 (2003).

[6] CKMfitter Group, J. Charles *et al.*, Eur. Phys. J. C **41**, 1 (2005).

[7] *BABAR* Collaboration, B. Aubert *et al.*, hep-ex/0507101.

[8] *BABAR* Collaboration, B. Aubert *et al.*, hep-ex/0408082. *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **71**, 031102 (2005). *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **72**, 032004 (2005). *BABAR* Collaboration, B. Aubert *et al.*, hep-ex/0504039, submitted to Phys. Rev. Lett.

[9] Belle Collaboration, K. Abe *et al.*, ICHEP04 8-0690 conference paper. Belle Collaboration, K. Abe *et al.*, hep-ex/0408129. Belle Collaboration, A. Poluektov *et al.*, Phys. Rev. D **70**, 072003 (2004). Belle Collaboration, K. Abe *et al.*, hep-ex/0411049. Belle Collaboration, K. Abe *et al.*, hep-ex/0504013.

[10] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **72**, 071103(R) (2005).

[11] *BABAR* Collaboration, B. Aubert *et al.*, Phys. Rev. D **72**, 071104(R) (2005).

[12] Particle Data Group, S. Eidelman *et al.*, Phys. Lett. B **592**, 1 (2004).