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Measurements of the CKM angle γ at *BABAR*

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We report on our recent measurements of the Cabibbo-Kobayashi-Maskawa *CP*-violating phase γ and of related *CP*-asymmetries and branching fraction ratios. The measurements have been performed on samples of up to 465 million $B\overline{B}$ pairs collected by the *BABAR* detector at the SLAC PEP-II asymmetric-energy B factory in the years 1999-2007.

1. INTRODUCTION

Within the Standard Model *CP* violation arises from a single irreducible complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-flavor-mixing matrix $V$and manifests itself as a non-zero area of the Unitarity Triangle (UT). This triangle depicts, in the complex plane, the relation $1+\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}+\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}=0$, that follows from the unitarity of V. The *BABAR* experiment has measured precisely, in $B \to (c\bar{c})X_s$ decays, the angle $\beta \equiv \arg -\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}$ of the UT, finding a value that differs significantly from 0 and π. This clearly indicates that the area of the UT is non-vanishing, thus establishing *CP*-violation. In order to confirm that the CKM mechanism is the correct explanation for *CP*-violation, we need to overconstrain the UT by measuring precisely the other angles (α and γ) and the sides.

2. MEASURING γ WITH B MESON DECAYS IN *BABAR*

The angle $\gamma \equiv \arg -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$ can be measured in a theoretically clean way in *CP*-violating B meson decays to open-charm final states, $D^{(*)}X_s$. In these decays the interference between the tree amplitudes $b \to c\bar{u}s$ and $b \to u\bar{c}s$ leads to observables that depend on the relative weak phase γ, the magnitude ratio $r_B \equiv \left|\frac{A(b\to u)}{A(b\to c)}\right|$ and the relative strong phase δ_B between the two amplitudes. r_B and δ_B depend on the B decay under investigation; they are difficult to estimate precisely from theory (QCD), but can be extracted directly from data together with γ.

In order to search for the interference between the $b \to c\bar{u}s$ and $b \to u\bar{c}s$ tree amplitudes, we have reconstructed the following decays, which lead to final states that can be produced both through $b \to c$ and $b \to u$ mediated processes: (i) charged $B \to D^{(*)0}/\overline{D}^{(*)0}K$ and $B \to D^0/\overline{D}^0K^*(K^* \to K^0_S\pi)$ decays and neutral $B^0 \to D^0/\overline{D}^0K^{*0}(K^{*0} \to K^+\pi^-)$ decays, followed by $D^{(*)0}$ meson decays to final states accessible also to $\overline{D}^{(*)0}$; (ii) neutral $B^0/\overline{B}^0$ decays to $D^{\pm}K^0\pi^{\mp}$. In the latter case, interference between the $b{\to}c$ and the $b{\to}u$ mediated processes is achieved through $B^0{-}\overline{B}^0$ mixing.

The measurements presented here exploit, partially or in total, the large data sample (465×10^6 $B\overline{B}$ pairs, assumed to be equally divided into B^+B^- and $B^0\overline{B}^0$) accumulated by *BABAR* in the years 1999-2007. Yet, they are still statistically limited, as the effects that are being searched for are tiny:

- The branching fractions of the B meson decays considered here are on the order of 5×10^{-4} ($B \to D^{(*)0}K$, D^0K^* and $DK^0\pi$) or 5×10^{-5} ($B^0 \to \overline{D}^0K^{*0}$). Branching fractions for $D^{(*)0}$ decays, including secondary decays, range between $O(10^{-2})$ and $O(10^{-4})$; D^- candidates are reconstructed in $K^-\pi^+\pi^+$ ($\mathcal{B} \approx 10\%$).

- The interference between the $b \to c$ and $b \to u$ mediated B decay amplitudes is predicted to be low, as the ratio r_B is expected to be around 40% for neutral $B^0 \to D^0K^{*0}$ and $DK^0\pi$ (due to CKM factors) and around 10% for charged $B \to D^{(*)0}K^{(*)}$ decays (due to CKM factors and the additional color-suppression of $A(b \to u)$).

The final states of these B meson decays are completely reconstructed, with efficiencies that range between 40% (for low-multiplicity, low-background decay modes) and 5% (for high-multiplicity decays). The selection is optimized in order to maximise the statistical sensitivity $S/\sqrt{S+B}$, where the number of expected signal (S) and background (B) events is estimated from simulated samples and data control samples.

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3. MEASUREMENTS OF γ WITH CHARGED B MESON DECAYS

3.1. Dalitz-plot method

On a sample of $383{\times}10^6$ $B\overline{B}$ pairs we have selected $B{\to}D^0K$, $D^{*0}K$ ($D^{*0}{\to}D^0\gamma$ and $D^0\pi^0$), and D^0K^*($K^*{\to}K^0_S\pi$) decays, followed by D^0 decays to the 3-body self-conjugate final states $K^0_S h^+h^-$ ($h=\pi, K$). [1] We have reconstructed 163 B candidates with $D^0 \to K^0_S KK$ and 979 B candidates with $D^0 \to K^0_S\pi\pi$. The channel $B \to D^0K^*, D^0 \to K^0_S K^+K^-$ has not been reconstructed due to lack of statistics. Following the approach proposed in [2], from a fit to the Dalitz-plot distribution of the D^0 daughters we have determined 2D confidence regions for the variables $(x_\pm, y_\pm)$, which are related to γ by $x_\pm \equiv r_B\cos(\delta_B \pm \gamma)$ and $y_\pm \equiv r_B \sin(\delta_B \pm \gamma)$. In the fit we have used a model for the D^0 and $\overline{D}^0$ decay amplitudes to $K^0_S h^+h^-$ described as the coherent sum of a non-resonant part and several intermediate two-body decays that proceed through known $K^0_S h$ or h^+h^- resonances. The model has been determined from large ($\approx 5.6\times 10^5$) and very pure ($\approx 98\%$) control samples of D mesons produced in $D^*{\to}D\pi$ decays.

The results for x and y are summarized in Table I. They are consistent with and have similar precision to those obtained by the Belle experiment. [3] From the $(x_\pm, y_\pm)$ confidence regions we determine, using a frequentist procedure, 1σ confidence intervals for γ, r_B and δ_B (Fig. 1). We obtain γ mod $180° = (76^{+23}_{-24})°$. The total error is dominated by the statistical contribution: the experimental and Dalitz-model-related systematic uncertainties amount to 5° each. We find values of r_B around 0.1, confirming that interference is low in these channels: $r_B^{D^0K} = 0.086{\pm}0.035$; $r_B^{D^{*0}K} = 0.135{\pm}0.051$; $kr_B^{D^0K^*} = 0.163^{+0.088}_{-0.105}$ (k=0.9±0.1 takes into account the K^* finite width). The small values of r_B favored by our data are responsible - since $\sigma_\gamma{\approx}\sigma_{x,y}/r_B$ - for the larger uncertainty on γ when compared to the analogous Belle measurement, which favours values of r_B about twice higher than ours. We also measure the strong phases (modulo 180°): $\delta_B^{D^0K}{=}(109^{+28}_{-31})°$; $\delta_B^{D^{*0}K}{=}(-63^{+28}_{-30})°$; $\delta_B^{D^0K^*}{=}(104^{+43}_{-41})°$. A 3σ evidence of direct CP violation is found when comparing (x_+, y_+) to (x_-, y_-) (they are equal in absence of CPV) in the three B decay channels.

Table I: Measurements of $x_\pm$ and $y_\pm$ obtained with the Dalitz and GLW analyses of $B \to D^{(*)0}K^{(*)}$

parameter	$B \to D^0K$	$B \to D^{*0}K$	$B \to D^0K^*$
x_+ (Dalitz)	$-0.067 \pm 0.043 \pm 0.014 \pm 0.011$	$0.137 \pm 0.068 \pm 0.014 \pm 0.005$	$-0.113 \pm 0.107 \pm 0.028 \pm 0.018$
x_+ (GLW)	$-0.09 \pm 0.05 \pm 0.02$	$0.09 \pm 0.07 \pm 0.02$	-
y_+ (Dalitz)	$-0.015 \pm 0.055 \pm 0.006 \pm 0.008$	$0.080 \pm 0.102 \pm 0.010 \pm 0.012$	$0.125 \pm 0.139 \pm 0.051 \pm 0.010$
x_- (Dalitz)	$0.090 \pm 0.043 \pm 0.015 \pm 0.011$	$-0.111 \pm 0.069 \pm 0.014 \pm 0.004$	$0.115 \pm 0.138 \pm 0.039 \pm 0.014$
x_- (GLW)	$0.10 \pm 0.05 \pm 0.03$	$-0.02 \pm 0.06 \pm 0.02$	-
y_- (Dalitz)	$0.053 \pm 0.056 \pm 0.007 \pm 0.015$	$-0.051 \pm 0.080 \pm 0.009 \pm 0.010$	$0.226 \pm 0.142 \pm 0.058 \pm 0.011$

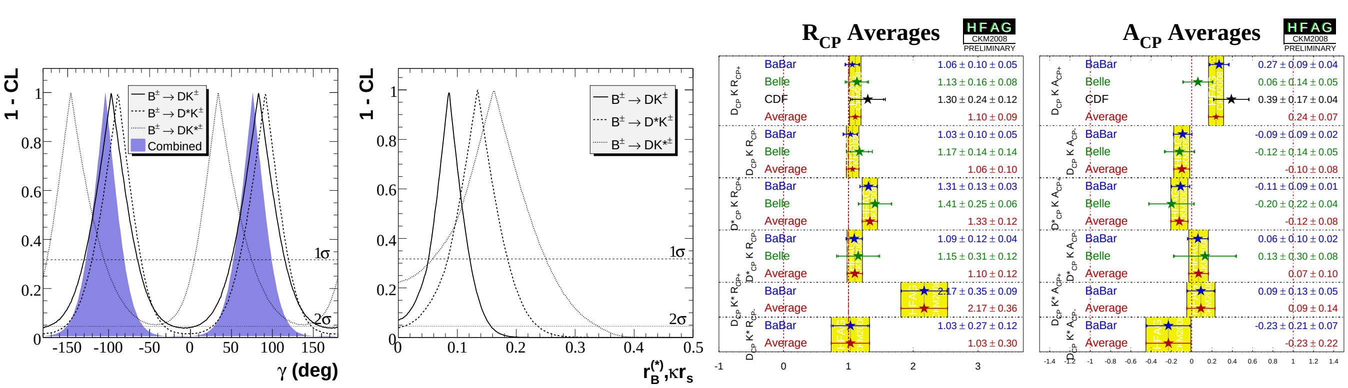

Figure 1: Two left-most plots: 1-CL as a function of γ and r_B for $B \to D^0K$, $D^{*0}K$ and D^0K^* as obtained with the Dalitz analysis of $D^0 \to K^0_S h^+h^-$. Two right-most plots: GLW observables measured by *BABAR* and other experiments.

3.2. Gronau-London-Wyler ("GLW") method

We have reconstructed, on a sample of 383×10^6 $B\overline{B}$ pairs, $B\to D^0K$ and $D^{*0}K$ ($D^{*0}\to D^0\gamma$ and $D^0\pi^0$) decays with neutral D mesons decaying to CP-even (K^+K^-, $\pi^+\pi^-$) and CP-odd ($K^0_S\pi^0$, $K^0_S\phi$ and $K^0_S\omega$) eigenstates. We have also reconstructed $B\to D^{(*)0}K$, $D^0\to K^-\pi^+$ and $B\to D^{(*)0}\pi$ decays as normalization channels. We have identified almost 500 $B\to D^0_{CP}K$ [4] and 500 $B\to D^{*0}_{CP}K$ [5] decays. From the observed $B^{\pm}$ yields we have determined the "GLW" observables [6], $R^{(*)}_{CP\pm}\equiv\frac{\Gamma(B^-\to D^{(*)0}_{CP\pm}K^-)+\Gamma(B^+\to D^{(*)0}_{CP\pm}K^+)}{(\Gamma(B^-\to D^{(*)0}K^-)+\Gamma(B^+\to\overline{D}^{(*)0}K^+))/2} = 1+{r^{(*)}_B}^2\pm2r^{(*)}_B\cos\gamma\cos\delta^{(*)}_B$ and $A^{(*)}_{CP\pm}\equiv\frac{\Gamma(B^-\to D^{(*)0}_{CP\pm}K^-)-\Gamma(B^+\to D^{(*)0}_{CP\pm}K^+)}{\Gamma(B^-\to D^{(*)0}_{CP\pm}K^-)+\Gamma(B^+\to D^{(*)0}_{CP\pm}K^+)} = \pm2r^{(*)}_B\sin\gamma\sin\delta^{(*)}_B/R^{(*)}_{CP\pm}$. Here we use the notation $r^{(*)}_B\equiv r_B^{D^{(*)0}K}$ and $\delta^{(*)}_B\equiv\delta_B^{D^{(*)0}K}$. The results, summarized in Table II and Fig. 1, constitute the most precise measurements of the CP asymmetries and branching fraction ratios in these decay channels. A 2.8σ hint of direct CPV is seen in $B\to D^0_{CP+}K$ decays, consistent with the results from the $B\to D^0K$, $D^0\to K^0_Sh^+h^-$ Dalitz analysis and with recent results of the GLW analysis of $B\to D^0_{CP+}K$ decays performed by CDF. From the relation ${r^{(*)}_B}^2=\frac{R^{(*)}_{CP+}+R^{(*)}_{CP-}-2}{2}$ we have obtained loose determinations of $r^{(*)}_B$: $(r_B^{D^0K})^2 = 0.05\pm0.07\pm0.03$, $(r_B^{D^{*0}K})^2 = 0.22\pm0.09\pm0.03$. We have also determined the variables $x_\pm$ by exploiting the relations $x_\pm=\frac{R_{CP+}(1\mp A_{CP+})-R_{CP-}(1\mp A_{CP-})}{4}$: the results, consistent with and similar in accuracy to those from the Dalitz analysis, are summarized in Table I. Due to a discrete 8-fold ambiguity on γ and the large uncertainty on $r^{(*)}_B$, the GLW results alone do not constrain γ, but are expected to improve the accuracy σ_γ of the Dalitz results presented in the previous section by a few degrees when combined with them.

Table II: Results of the $B\to D^0K$ and $B\to D^{*0}K$ GLW analyses

B **decay**	$A^{(*)}_{CP+}$	$R^{(*)}_{CP+}$	$A^{(*)}_{CP-}$	$R^{(*)}_{CP-}$
D^0K	$0.27\pm0.09\pm0.04$	$1.06\pm0.10\pm0.05$	$-0.09\pm0.09\pm0.02$	$1.03\pm0.10\pm0.05$
$D^{*0}K$	$-0.11\pm0.09\pm0.01$	$1.31\pm0.13\pm0.04$	$0.06\pm0.10\pm0.02$	$1.10\pm0.12\pm0.04$

4. MEASUREMENTS OF γ WITH NEUTRAL B MESON DECAYS

4.1. $B^0\to\overset{(-)}{D}{}^0K^{*0}$: Atwood-Dunietz-Soni ("ADS") and Dalitz-plot methods

In the "ADS" analysis [8] we reconstruct D^0 decays to doubly-Cabibbo-suppressed final states: $K^+\pi^-$, $K^+\pi^-\pi^0$ and $K^+\pi^-\pi^-\pi^+$. The Cabibbo-allowed charge-conjugate final states are used as normalization and control sample. In principle γ could be determined from the branching fraction ratios (R_{ADS}) and the charge asymmetries (A_{ADS}) of these decays. [7] In practice we do not have enough statistics to measure A_{ADS} and put useful constraints on γ; on the other hand by measuring R_{ADS} we can infer a significant constraint on $r_S\equiv r_B^{D^0K^{*0}}$. We have selected, on a sample of 465×10^6 $B\overline{B}$ pairs, 24 signal candidates summed over the 3 D^0 decay channels, and put 95% probability bayesian limits on R_{ADS}: $R^{K\pi}_{ADS}<0.244$; $R^{K\pi\pi^0}_{ADS}<0.181$; $R^{K\pi\pi\pi}_{ADS}<0.391$. We have then combined those 3 results and determined bayesian probability regions for r_S by adding external information (from c- and B-factories) on the $\overset{(-)}{D}{}^0$ decay amplitudes. At 95% probability r_S lies between 7 and 41% (Fig. 2).

In the Dalitz analysis [9] we reconstruct $\overset{(-)}{D}{}^0$ decays to $K^0_S\pi^+\pi^-$. Using 371×10^6 $B\overline{B}$ pairs we have selected 39 signal candidates. From the fit to the Dalitz-plot distribution of the D^0 daughters, using the same model for the $\overset{(-)}{D}{}^0\to K^0_S\pi^+\pi^-$ decay amplitudes as in Sec. 3.1, we have determined 2D bayesian probability regions for (r_S,γ) (Fig. 2). After combination with the r_S likelihood from the ADS method we obtain, at 68% probability, $\gamma \bmod 180^\circ=(162\pm56)^\circ$.

4.2. $2\beta+\gamma$ from a time-dependent Dalitz-plot analysis of $B^0/\overline{B}^0\to D^\pm K^0\pi^\mp$

On a sample of 347×10^6 $B\overline{B}$ pairs we have searched for neutral B meson decays to $D^\pm K^0_S\pi^\mp$. [10] We retain only those events where the other B meson ($B_{\rm tag}$) decays to a final state which allows to determine its flavor

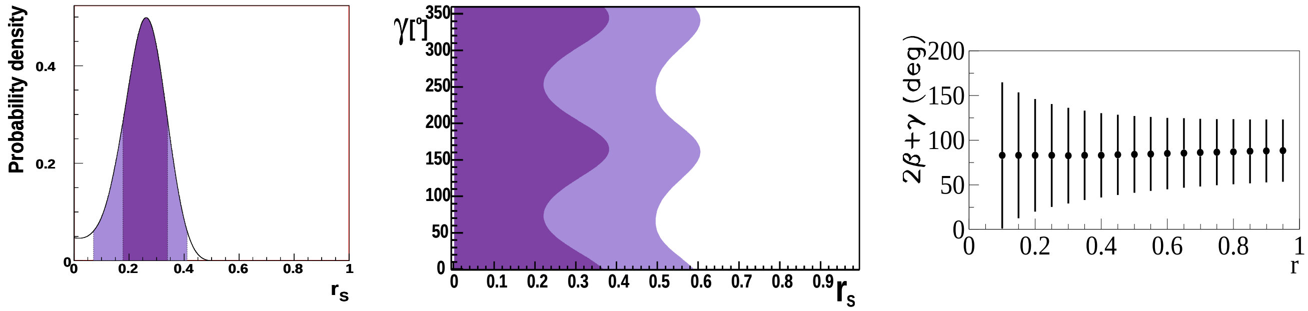

Figure 2: Left: likelihood function for r_S from the ADS analysis of $B^0 \to D^0 K^{*0}$, including 68% (dark-shaded) and 95% (light-shaded) probability regions. Center: γ vs r_S 68% and 95% probability regions obtained from the $B^0 \to D^0 K^{*0}$ Dalitz analysis. Right: distribution of the fitted values of $2\beta+\gamma$ from selected $B^0 \to DK^0\pi$ decays for different hypotheses on the value of r.

(either B^0 or $\overline{B}^0$) and the proper time difference Δt between the two B decays, inferred from the separation of the B decay vertices and momenta. The effective efficiency of the flavor-tagging algorithm is around 30%. A fit to the Dalitz-plot distribution of $DK^0_s\pi$ as a function of Δt yields $2\beta+\gamma$ through the relations: $\Gamma(\vec{x}, \Delta t, \xi, \eta) = \frac{A_c(\vec{x})^2 + A_u(\vec{x})^2}{2} \times \frac{e^{-\frac{|\Delta t|}{\tau_B}}}{4\tau_B} \times \{1 - \eta\xi C(\vec{x}) \cos(\Delta m_d \Delta t) + \xi S_\eta(\vec{x}) \sin(\Delta m_d \Delta t)\}$, $S_\eta(\vec{x}) = \frac{2\Im(A_c(\vec{x}) A_u(\vec{x}) e^{i(2\beta+\gamma)+\eta i(\phi_c(\vec{x}) - \phi_u(\vec{x}))})}{A_c(\vec{x})^2 + A_u(\vec{x})^2}$, $C(\vec{x}) = \frac{A_c(\vec{x})^2 - A_u(\vec{x})^2}{A_c(\vec{x})^2 + A_u(\vec{x})^2}$. τ_B is the B^0 lifetime, Δm the $B^0 - \overline{B}^0$ mixing frequency, $\vec{x}$ the position in the $DK\pi$ Dalitz plot; $\xi = -1(1)$ if the flavor of the $B_{\rm tag}$ is $B^0(\overline{B}^0)$, and $\eta = +1(-1)$ if the final state contains a $D^+(D^-)$.

We have selected 558 signal candidates and performed the time-dependent Dalitz-plot fit. For the direct B decay amplitude we use a model which incorporates all known intermediate resonances and float most of the magnitudes (A) and phases (ϕ) in the fit. The ratio r between the $b \to u$ (A_u) and $b \to c$ (A_c) amplitudes is fixed. A scan of $2\beta+\gamma$ as a function of r is shown in Fig. 2. For the final $2\beta+\gamma$ result we assume $r = 0.3 \pm 0.1$. Using the world average for β from B decays to charmonium we obtain γ mod $180^\circ = (40 \pm 57)^\circ$, in agreement with the other determinations.

5. CONCLUSION

Many new results on γ have been obtained by *BABAR* during 2008. They are in good agreement with each other and favor $\gamma \approx 72^\circ$, dominated by the $B \to D^{(*)0} K^*$, $D^0 \to K^0_S h^+ h^-$ Dalitz analysis and consistent with expectations from CKM fits. Thanks to the combination of several strategies, the uncertainty σ_γ is approaching 20°, which was not an original goal of the B factories. σ_γ is limited by the available statistics; we expect a 20% improvement from the collected data that have not been analyzed yet. The interference effects are confirmed to be small both in charged and neutral B decays, thus a much larger statistics is needed to reach a precision of a few degrees on γ.

References

[1] *BaBar* Collaboration, B. Aubert *et al.*, *Phys. Rev.* **D78**, 034023 (2008).
[2] A. Giri, Y. Grossman, A. Soffer and J. Zupan, *Phys. Rev.* **D68**, 054018 (2003).
[3] Belle Collaboration, K. Abe *et al.*, arXiv:0803.3375 [hep-ex] (2008).
[4] *BaBar* Collaboration, B. Aubert *et al.*, *Phys. Rev.* **D77**, 111102(R) (2008).
[5] *BaBar* Collaboration, B. Aubert *et al.*, arXiv:0807.2408 [hep-ex]. Submitted to *Phys. Rev.* **D** (2008).
[6] M. Gronau and D. Wyler, *Phys. Lett.* **B265**, 172; M. Gronau and D. London, *Phys. Lett.* **B253**, 483 (1991).
[7] D. Atwood, I. Dunietz and A. Soni, *Phys. Rev. Lett.* **78**, 3257 (1997).
[8] *BaBar* Collaboration, B. Aubert *et al.*, paper in preparation.
[9] *BaBar* Collaboration, B. Aubert *et al.*, arXiv:0805.2001 [hep-ex], submitted to *Phys. Rev.* **D** (2008)
[10] *BaBar* Collaboration, B. Aubert *et al.*, *Phys. Rev.* **D77**, 071102(R) (2008).