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MEASUREMENTS OF γ IN *BABAR*

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We report on the first measurements ot the angle γ of the Unitarity Triangle in B meson decays collected by the *BABAR* detector at the SLAC PEP-II asymmetric-energy B factory in the years 1999-2004.

1. Introduction

A stringent test of the flavor and CP sector of the Standard Model can be obtained from the measurement, in B meson decays, of the sides and angles of the Unitarity Triangle, which are related to the elements of the Cabibbo-Kobayashi-Maskawa quark-mixing matrix V. Among the angles, $\gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$ is the most difficult to measure, since the B decay modes that provide information on it are characterized either by very small branching fractions, small interference effects or low reconstruction efficiencies.

2. General strategies for measuring γ from B meson decays

γ is the relative weak phase between the tree amplitudes $b \to c\bar{u}q$, $q = \{s, d\}$ ($\propto V_{cb}V_{uq}^*$), and $b \to u\bar{c}q$ ($\propto V_{ub}V_{cq}^*$), and can be measured using CP-violating B decays where the two processes interfere. Since no penguin amplitudes are involved, these approaches are unaffected by a large class of possible new-physics effects. In *BABAR*,[1] B^+B^- and $B^0\bar{B}^0$ pairs are produced in $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ collisions at $\sqrt{s} = 10.58$ GeV. The total amount of $B\bar{B}$ pairs collected in the years 1999-2004 is 232×10^6, equally divided into B^+B^- and $B^0\bar{B}^0$. Within this sample we search for CP-violation in $B^- \to D^{(*)0}K^{(*)-}$ ($q = s$) and $B^0 \to D^{(*)\pm}\pi^{\mp}$ ($q = d$) decays.

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3. Measuring γ in charged $B \to D^{(*)0}K^{(*)}$ decays

Interference in charged $B{\to}D^{(*)0}K^{(*)}$ decays occurs when $D^{*0}{\to}D^0\pi^0$ or $D^0\gamma$, and the D^0 final state is also accessible to $\bar{D}^0$. This can be either a singly Cabibbo-suppressed CP eigenstate like K^+K^- (GLW method[2]), a doubly Cabibbo-suppressed flavor eigenstate like $K^+\pi^-$ (ADS method[3]), or a Cabibbo-allowed multi-body state like $K^0_S\pi^+\pi^-$ (GGSZ method[4]). By measuring the time-independent rates and CP asymmetries, γ can be determined together with hadronic quantities (the ratio r_B of the magnitudes of the $B^-{\to}\bar{D}^0K$ and $B^-{\to}D^0K$ amplitudes and their strong phase difference δ_B) that would otherwise need to be calculated from QCD. The γ-related experimental observables[a] in the GLW method are:[b]

$$R_{CP\pm} \equiv \frac{\Gamma(B^-{\to}D^0_{CP\pm}K^-) + \Gamma(B^+{\to}D^0_{CP\pm}K^+)}{\Gamma(B^-{\to}D^0K^-) + \Gamma(B^+{\to}\bar{D}^0K^+)}, \tag{1}$$

$$A_{CP\pm} \equiv \frac{\Gamma(B^-{\to}D^0_{CP\pm}K^-) - \Gamma(B^+{\to}D^0_{CP\pm}K^+)}{\Gamma(B^-{\to}D^0_{CP\pm}K^-) + \Gamma(B^+{\to}D^0_{CP\pm}K^+)}, \tag{2}$$

where $D^0_{CP\pm}$ denotes a CP-even (+) or CP-odd (−) D^0 decay. The interference term sensitive to γ is proportional to r_B, which from CKM and color suppression is expected to be $\approx 10\%$. The γ-related ADS observables are:[c]

$$R_{\rm ADS} \equiv \frac{\Gamma(B^-{\to}D^0[K^+\pi^-]K^-) + \Gamma(B^+{\to}\bar{D}^0[K^-\pi^+]K^+)}{\Gamma(B^-{\to}D^0[K^-\pi^+]K^-) + \Gamma(B^+{\to}\bar{D}^0[K^+\pi^-]K^+)}, \tag{3}$$

$$A_{\rm ADS} \equiv \frac{\Gamma(B^-{\to}D^0[K^+\pi^-]K^-) - \Gamma(B^+{\to}\bar{D}^0[K^-\pi^+]K^+)}{\Gamma(B^-{\to}D^0[K^+\pi^-]K^-) + \Gamma(B^+{\to}\bar{D}^0[K^-\pi^+]K^+)}. \tag{4}$$

To extract γ, the quantity $r_D \equiv |A(D^0{\to}K^+\pi^-)/A(D^0{\to}K^-\pi^+)|$ must also be known. The interference term is proportional to $r_B/r_D = \mathcal{O}(1)$, but branching fractions are suppressed with respect to the previous case by a factor ≈ 25. In the GGSZ method γ is extracted from the Dalitz distribution, for positive and negative $B{\to}D^0K$ candidates, of the D^0 decay products.[d] Interference and hence the sensitivity to γ vary across the Dalitz plot. Branching fractions are 1-2 orders of magnitude higher than in previous cases, but a more complicated study is required and, within the present statistics, the full Dalitz D^0 decay amplitude must be known.

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[a] Here and throughout the text we write only the explicit formulae for $B{\to}D^0K$.
[b] $R_{CP\pm} = 1 + r_B^2 \pm 2r_B\cos\gamma\cos\delta_B,\ A_{CP\pm} = \pm 2r_B\sin\gamma\sin\delta_B/R_{CP\pm}$
[c] $R_{\rm ADS} = r_B^2 + r_D^2 + 2r_Br_D\cos\gamma\cos\delta'_B,\ A_{\rm ADS} = 2r_Br_D\sin\gamma\sin\delta'_B/R_{\rm ADS},\ \delta'_B = \delta_B + \arg[A(D^0 \to K^+\pi^-)/A(D^0 \to K^-\pi^+)]$
[d] $A(B^\pm{\to}D^0[K^0_S\pi^+\pi^-]K)(m^2_-, m^2_+) \propto [f(m^2_\pm, m^2_\mp) + r_Be^{i\delta_B}e^{\pm i\gamma}f(m^2_\mp, m^2_\pm)]$. $m_\pm$ are the $K^0_S\pi^\pm$ invariant masses, $f(m^2_+, m^2_-)$ is the Dalitz $D^0{\to}K^0_S\pi^+\pi^-$ amplitude.

In *BABAR*, the GLW analysis has been performed for the channels $B \to D^0_{CP\pm}K$ (see Figure 1),[5] $B \to D^0_{CP\pm}K^*$,[6] and $B \to D^{*0}_{CP+}K$.[7] The ADS analysis has been performed for $B \to D^{(*)0}K$, $D^{*0} \to D^0\pi^0$ and $D^0\gamma$, $D^0 \to K^+\pi^-$ decays.[8] The GGSZ analysis has been performed for $B \to D^{(*)0}K$, $D^{*0} \to D^0\pi^0$ and $D^0\gamma$, $D^0 \to K^0_S\pi^+\pi^-$ decays.[9] The full decay chains are reconstructed and B meson candidates with beam-energy-substituted mass ($m_{\rm ES}$) and center-of-mass (CM) energy (E^*_B) consistent with $m_B = 5279$ GeV/c^2 and $\sqrt{s}/2$ are selected. Combinatorial background from $e^+e^- \to q\bar{q}$ processes ($q = u, d, s, c$) is suppressed by exploiting the different CM topologies of $B\bar{B}$ (spherical) and $q\bar{q}$ (jet-like) events. Particle identification information allows to distinguish between $B \to D^{(*)0}K$ and ≈ 12 times more abundant $B \to D^{(*)0}\pi$ decays. We reconstruct 93±15 $B \to D^0_{CP+}[K^+K^-, \pi^+\pi^-]K$ and 76±13 $B \to D^0_{CP-}[K^0_S\pi^0]K$ in a sample of 214×10^6 $B^\pm$, 35±7 $B \to D^0_{CP+}[K^+K^-, \pi^+\pi^-]K^*$ and 15±6 $B \to D^0_{CP-}[K^0_S\pi^0, K^0_S\phi, K^0_S\omega]K^*$ in a sample of 227×10^6 $B^\pm$, and 30±7 $B \to D^{*0}_{CP+}[D^0_{CP+}\pi^0]K$, $D^0_{CP+} \to K^+K^-, \pi^+\pi^-$ in a sample of 130×10^6 $B^\pm$. In the ADS modes no signal is found in a sample of 227×10^6 $B^\pm$. 282 ± 20 $B \to D^0K$, 83 ± 11 $B \to D^{*0}[D^0\pi^0]K$ and 40 ± 8 $B \to D^{*0}[D^0\gamma]K$, $D^0 \to K^0_S\pi^+\pi^-$ candidates are found in a sample of 211×10^6 $B^\pm$. The measured value of R_{CP}, A_{CP} and $R_{\rm ADS}$ are summarized in Table 1; no $A_{\rm ADS}$ measurement is possible with the current data sample. $r_D = 0.060 \pm 0.003$[10] is measured on a clean sample of $D^{*+} \to D^0\pi^+, D^0 \to K\pi$ decays produced in $e^+e^- \to c\bar{c}$ events. In the GGSZ approach, the $D^0 \to K^0_S\pi^+\pi^-$ amplitude is determined on a large, 97% pure sample of 81500 reconstructed $D^{*+} \to D^0\pi^+, D^0 \to K^0_S\pi^+\pi^-$ decays, and from the Dalitz distribution of D^0 mesons from $B \to D^{(*)0}K$ decays a 68% C.L. interval for γ is found, up to a 180° ambiguity: $\gamma = (70 \pm 26 \pm 14)^\circ$. When combining this result with the information from the GLW and ADS measurements, the 68% C.L. interval for γ – evaluated by the UTFit collaboration[11] – is, modulo 180°, $\gamma = (60 \pm 29)^\circ$ or $\gamma = (107 \pm 6)^\circ$. The parameter r_B is found to be < 0.16 for D^0K and $D^{*0}K$ and < 0.74 for D^0K^* at 95% C.L.

Table 1. Measured γ-related observables in $B \to D^{(*)}K^{(*)}$ GLW and ADS analyses.

	R_{CP+}(%)	A_{CP+}(%)	R_{CP-}(%)	A_{CP-}(%)	$R_{\rm ADS}$(%)
D^0K	87±14±6	40±15±8	80±14±8	21±17±7	$1.3^{+1.1}_{-0.9}$
D^0K^*	173±36±11	−8±20±6	64±25±7	−35±38±10	-
$D^{*0}(D^0\pi^0)K$	106±26±10	−10±23±4	-	-	$-0.1^{+1.0}_{-0.6}$
$D^{*0}(D^0\gamma)K$	-	-	-	-	$1.1^{+1.9}_{-1.3}$

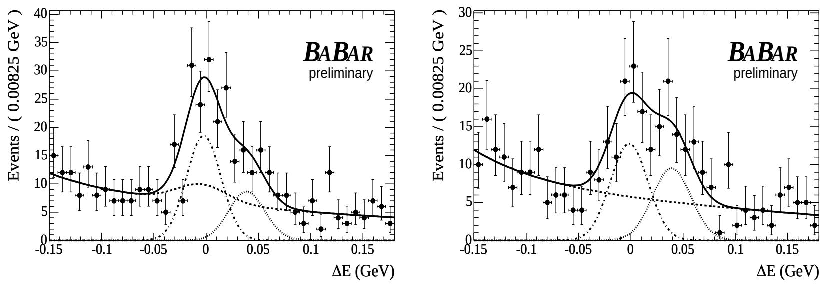

Figure 1. $\Delta E(\equiv E_B^* - \sqrt{s}/2)$ distribution of $B \to D^0_{CP+} K$ (right) and $B \to D^0_{CP-} K$ (left) candidates. Solid curves are projections of a maximum likelihood fit; dash-dotted, dotted and dashed curves represent the $B \to D^0 K$, $B \to D^0 \pi$ and background contributions.

4. Measuring $2\beta + \gamma$ in neutral $B^0 \to D^{(*)\pm}\pi^\mp$ decays

$B^0 - \bar{B}^0$ mixing can lead to interference between the $(b \to c\bar{u}d)$ $B^0 \to D^{(*)-}\pi^+$ and $(b \to u\bar{c}d)$ $\bar{B}^0 \to D^{(*)-}\pi^+$ amplitudes.[12] When the other B from the same $\Upsilon(4S)$ decay is reconstructed in a flavor-specific state (like $D^{*+}e^-\bar{\nu}_e$) and the proper time difference Δt of the two B decay instants is inferred from the measured distance between the decay vertices and from the known $\Upsilon(4S)$ boost ($\beta_\Upsilon \approx 0.49$), $2\beta + \gamma$ can be obtained from the time-dependent CP asymmetries:

$$\mathcal{A}_\pm(\Delta t) \equiv \frac{N(B^0(\Delta t) \to D^{(*)\pm}\pi^\mp) - N(\bar{B}^0(\Delta t) \to D^{(*)\pm}\pi^\mp)}{N(B^0(\Delta t) \to D^{(*)\pm}\pi^\mp) + N(\bar{B}^0(\Delta t) \to D^{(*)\pm}\pi^\mp)}, \qquad (5)$$

where $B^0(\Delta t)$ means that the other B has decayed to a final state accessible only to $\bar{B}^0$ and viceversa. Since $\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$ is accurately measured in neutral $B^0 \to (c\bar{c})K^{(*)0}$ decays (at present $\sigma_\beta \approx 1.5°$), this leads to a measurement of γ. Branching fractions are at least an order of magnitude higher than in $B \to D^{(*)}K^{(*)}$, but the interfering amplitudes differ by a factor $r_B(D^{(*)}\pi) \equiv |A(\bar{B}^0 \to D^{(*)-}\pi^+)/A(B^0 \to D^{(*)-}\pi^+)| = \mathcal{O}(|V_{ub}V_{cd}^*|/|V_{cb}V_{ud}^*|) \approx 0.02$ and therefore the sensitivity to γ is very small.

In *BABAR* $B^0 \to D^*\pi$ decays have been reconstructed on a sample of 89×10^6 $B^0\bar{B}^0$ pairs with a partial reconstruction technique.[13] The asymmetries $\mathcal{A}_\pm(\Delta t)$ have been measured (see Fig. 2). From these asymmetries, fixing the value $r_B(D^*\pi) = (1.5^{+0.4}_{-0.6} \pm 0.5)\%$ obtained from the $B^0 \to D_s^{*+}\pi^-$ and $B^0 \to D^{*-}\pi^+$ branching fractions assuming SU(3) factorization, the limit $|\sin(2\beta + \gamma)| > 0.75(0.58)$ at 68%(90%) C.L. is found.

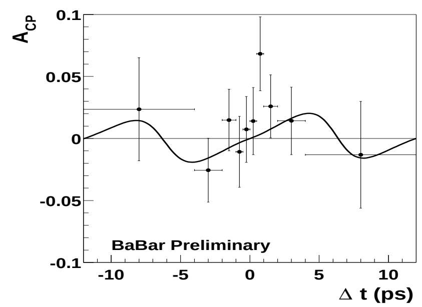

Figure 2. $B^0 \to D^{*-}\pi^+$ time-dependent *CP* asymmetry for events in which the flavor of the other B is inferred from the charge of the high-momentum lepton produced in a semileptonic decay. Solid curves represent the projections of a maximum likelihood fit

5. Conclusions

The angle γ is the most difficult of the Unitarity Triangle angles to measure with B mesons. The interference terms sensitive to γ are proportional to a small quantity r_B ($0.02 - 0.2$ according to the B decay mode considered). By combinining several approaches *BABAR* has measured γ with $\approx 30°$ precision. The enlarged data sample available in the future and the measurement of additional γ-related observables will lead to a more accurate determination of γ, up to $12 - 15°$ by year 2008. A precise measurement of γ is essential for a critical test of the Standard Model flavor sector.

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