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MEASUREMENT OF THE CKM ANGLES α AND γ AT THE *BABAR* EXPERIMENT

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We present recent measurements of the CKM angles α and γ using data collected by the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider at the Stanford Linear Accelerator Center. In addition to constraints on α from the decays $B^0 \to \pi^+\pi^-$, $B^0 \to \rho^\pm\pi^\mp$, and $B^0 \to \rho^+\rho^-$, we also report the first measurement of time-dependent *CP* asymmetries in the decay $B^0 \to a_1^\pm(1260)\pi^\mp$. We present measurements of γ in $B^\pm \to D^{(*)0}K^\pm$ decays using a Dalitz analysis in the modes $D^0 \to K_s\pi^+\pi^-$ and $D^0 \to \pi^+\pi^-\pi^0$.

1. Introduction

The measurements of the angles α, β and γ of the Unitarity Triangle (UT) at the B-factories are providing precision tests of the description of *CP* violation in the Standard Model (SM). This description is provided by the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix[1,2]. I am summarizing here the experimental constraints on the Unitarity Triangle angle α and γ obtained from B meson decays with the *BABAR* experiment at SLAC. The *BABAR* detector and PEP-II accelerator are described elsewhere[3].

2. Measurements of the angle α

The decays of neutral B mesons to the final states hh', where h^+, h'^-=π, ρ, a_1 are sensitive to the CKM angle α in the interference between decay and mixing [4]. The presence of gluonic loop ("penguin") contributions with a different weak phase to the tree contribution shifts the measured angle from the UT angle α to an effective parameter α_{eff}, where the shift is defined

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as $\delta\alpha = \alpha - \alpha_{eff}$. The time-dependent *CP* asymmetry has the form:

$$\mathbf{A}(\mathbf{t}) = S\sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t) \tag{1}$$

where Δm_d is the $B\bar{B}$ mixing frequency, Δt is the proper time difference between the decay of the two B mesons in an event and the coefficients are given by:

$$S = \frac{2\mathrm{Im}(\lambda)}{1+|\lambda|^2}, \quad C = \frac{1-|\lambda|^2}{1+|\lambda|^2}, \quad \lambda = \frac{q}{p}\frac{\bar{A}}{A} = e^{2i\alpha}\frac{1-\frac{P}{T}e^{-i\alpha}}{1-\frac{P}{T}e^{+i\alpha}} = |\lambda|e^{2i\alpha_{\mathrm{eff}}} \tag{2}$$

where q and p are the B mixing coefficients and $\frac{P}{T}$ is the penguin to tree amplitude ratio, which can be different for $\pi\pi$, $\rho\pi$, $\rho\rho$ and $a_1\pi$. Either isospin symmetry [5,6] or broken SU(3) flavor symmetry [7] can be employed to disentangle α from α_{eff}.

2.1. $B \rightarrow \pi\pi$ *and* $B \rightarrow \rho\rho$

The measurements of the various branching fractions and *CP* asymmetries measured in $B \rightarrow \pi\pi$ and $B \rightarrow \rho\rho$ are summarized in Tab. 1, A_{CP} is the charge (tag) asymmetry in the case of a charged (neutral) B decay. The measurements are sufficiently well established to perform an isospin analysis. However, the value of $\mathfrak{B}(B \rightarrow \pi^0\pi^0)$ is the limiting factor in the $B \rightarrow \pi\pi$ isospin analysis; its value is too large to allow a tight bound to be placed on $\delta\alpha$ [8]. The present measurement excludes the absence of *CP* violation ($S_{\pi\pi} = 0$, $C_{\pi\pi} = 0$) at a C.L. of 3.6 σ. The limit that results from the current isospin analysis is $\delta\alpha^{\pi\pi} < 41°$ at 90% C.L[8].

Table 1. Summary of *BABAR* measurements of $B \rightarrow \pi\pi$ and $B \rightarrow \rho\rho$ decays.

Mode	$\mathfrak{B}(10^{-6})$	S	C
$\pi^+\pi^-$	$4.7 \pm 0.6 \pm 0.2$	$-0.53 \pm 0.14 \pm 0.02$	$-0.16 \pm 0.11 \pm 0.03$
$\rho^+\rho^-$	$23.5 \pm 2.2 \pm 4.1$	$-0.19 \pm 0.2\,^{+0.05}_{-0.07}$	$-0.07 \pm 0.15 \pm 0.06$
		A_{CP}	
$\rho^\pm\rho^0$	$16.8 \pm 2.2 \pm 2.3$	$-0.12 \pm 0.13 \pm 0.10$	
$\rho^0\rho^0$	$1.07 \pm 0.33 \pm 0.19$	—	
$\pi^\pm\pi^0$	$5.12 \pm 0.47 \pm 0.29$	$-0.01 \pm 0.10 \pm 0.02$	
$\pi^0\pi^0$	$1.48 \pm 0.26 \pm 0.12$	$-0.33 \pm 0.36 \pm 0.08$	

The analysis of $B \rightarrow \rho\rho$ is potentially complicated due to the possible presence of three helicity states for the decay. The helicity zero state, which corresponds to longitudinal polarization of the decay, is *CP*-even but the helicity ± 1 states are not *CP* eigenstates. Fortunately this complication is avoided due to the experimental determination that the longitudinally polarized fraction is dominant $f_L = 0.977 \pm 0.024(stat)^{+0.015}_{-0.013}(syst)$. This and other $\rho\rho$ measurements are summarised in Tab. 1. The measurements of the branching fractions of $B \to \rho^{\pm}\rho^{0}$ and $B \to \rho^{0}\rho^{0}$ indicate that the penguin pollution is small in these modes compared with $B \to \pi\pi$ decays [10 11]. As such it is possible to perform an isospin analysis on the longitudinal part of the decay and to place a much tighter bound on $\delta\alpha^{\rho\rho}$; the measured *CP* violating parameters in $B \to \rho^{+}\rho^{-}$ corresponds to $\alpha^{\rho\rho}_{eff} = (95.5\ ^{+6.9}_{-6.2})^{\circ}$ and the limit that results from the current isospin analysis is $\delta\alpha^{\rho\rho} < 20^{\circ}$ at 90% confidence level (C.L.)[11].

2.2. $B \to \rho\pi$ *and* $B \to a_1\pi$

The $B \to \rho\pi$ measurement reported here is a time-dependent Dalitz plot analysis. We model the interference between the intersecting ρ resonance bands and so determins the strong phase differences from the Dalitz plot structure[13]. The Dalitz amplitudes and time-dependence are contained in complex parameters that are determined by a likelihood fit. The values obtained for these parameters are then converted back into the quasi-two-body *CP* observables, S, C, ΔS, ΔC and A_{CP} which are more intuitive in their interpretation[14].

Table 2. Summary of the *BABAR* quasi-two-body *CP* observables in $B \to \rho\pi$ and $B \to a_1\pi$ decays. The parameters ΔS and ΔC are insensitive to *CP* violation.

Mode	S	C	A_{CP}
$\rho^{\pm}\pi^{\mp}$	$0.010 \pm 0.120 \pm 0.028$	$0.154 \pm 0.090 \pm 0.037$	$-0.142 \pm 0.041 \pm 0.015$
$a_1^{\pm}\pi^{\mp}$	$0.37 \pm 0.21 \pm 0.07$	$-0.10 \pm 0.15 \pm 0.09$	$-0.07 \pm 0.07 \pm 0.02$
	ΔS	ΔC	
$\rho^{\pm}\pi^{\mp}$	$0.060 \pm 0.130 \pm 0.029$	$0.377 \pm 0.091 \pm 0.021$	
$a_1^{\pm}\pi^{\mp}$	$-0.14 \pm 0.21 \pm 0.06$	$0.26 \pm 0.15 \pm 0.07$	

Using these results we obtain $\alpha^{\rho\pi} \in (75{,}152)^{\circ}$ at 68% C.L. This result is of particular interest because there is a unique solution between 0 and 180°, which helps to break the ambiguity on the $\rho\rho$ result, which is in itself more precise. We get a hint of direct *CP* violation at the 3.0 σ level.

The first measurements of *CP*-violating asymmetries in $B \to a_1\pi$ decays with $a_1^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm}$ have recently been performed by *BABAR* using a "quasi-two-body"approach[15]. A full isospin analysis requires the precise measurements of the branching fractions and asymmetries in the five modes $B^0 \to a_1^+\pi^-, a_1^-\pi^+, a_1^0\pi^0, B^+ \to a_1^+\pi^0, a_1^0\pi^+$ and in the charged conjugate modes. However, even measuring all the branching fractions and time-dependent *CP* asymmetries in the three B^0 decay modes, this isospin method for extracting the angle α is not feasible with the present statistics. Assuming flavor SU(3) symmetry one can determine an upper bound on $\delta\alpha^{a_1\pi}$ using SU(3) related decays to $a_1\pi$ [16]. The measured *CP* parameters in this mode are shown in Tab. 2. Using these quatities $\alpha_{eff}^{a_1\pi} = (78.6 \pm 7.3)^\circ$ has been extracted [15]. Once the measurements of branching fractions for the SU(3)-related decays become available, an upper bound on $\delta\alpha^{a_1\pi}$ will provide a constraint on the angle α.

3. Measurements of the angle γ

Sensitivity to the CKM angle γ occurs in decay modes that have contributions from diagrams containing $b \to c$ and $b \to u$ transitions that interfere with eachother. The size of the interference, and hence the sensitivity to γ, is determined by the relative magnitudes of the two processes. The two diagrams considered here are those of $B^+ \to \overline{D}^0 K^+$ and $B^+ \to D^0 K^+$. In order for these two processes to interfere it is required that the final state be the same. Here we examine the decay of the D^0 and $\overline{D}^0$ to $K_S^0\pi^+\pi^-$. In this decay mode, there are four unknowns γ, $r_B \equiv \frac{|A(B^+ \to D^0 K^+)|}{|A(B^+ \to \overline{D}^0 K^+)|}$, δ_B (the strong phase of the B decay) and δ_D (the strong phase of the D decay). This last parameter is eliminated by using the Dalitz plot structure of the $D^0 \to K_S^0\pi^+\pi^-$ decay in the likelihood fit. This is determined by performing a full Dalitz plot analysis of this D decay mode using a very high statistics sample of D^{*+} decays. The resulting amplitude model is then fixed in the fit. A simultaneous fit is then performed to the B^+ and B^- data samples in order to determine γ, δ_B and r_B. In addition to the Dalitz plot information, kinematic and event topology information is used to separate the signal and background events [18]. We obtain $\gamma = (92 \pm 41(stat) \pm 11(syst) \pm 12(theo))^\circ$. Preliminary results in $B^- \to D^0 K^-$ decays with $D^0 \to K^-\pi^+\pi^0$ and $D^0 \to \pi^+\pi^-\pi^0$ have been presented, their effect on γ have not been evaluated yet [19,20].

4. Summary

The *BABAR* experiment has conducted several analyses with the aim of extracting α and γ. In the last few years the measurements of the angles of the CKM Unitarity Triangle have become increasingly sophisticated and precise. At present the *BABAR* measurement of the alpha and gamma angles are in a good agreement with the predictions obtained by SM-based fits.

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