MEASUREMENTS OF CKM ANGLE β FROM *BABAR*

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We present recent results of hadronic B meson decays related to the CKM angle β. The data used were collected by the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider operating at the $\Upsilon(4S)$ resonance located at the Stanford Linear Accelerator Center.

1. Introduction

The Standard Model (SM) of particle physics describes charge conjugation-parity (CP) violation as a consequence of a complex phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix[1]. CP violation in B meson decays is described by the angles α, β and γ of the Unitarity Triangle. We describe here recent results from *BABAR* for the angle β, defined as $\arg\left[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right]$ where the V_{ij} are CKM matrix elements.

The *BABAR* detector[2] is located at the SLAC PEP-II e^+e^- asymmetric-energy B-factory[3]. Data are collected at the $\Upsilon(4S)$ resonance.

These proceedings describe measurements of $\sin2\beta$ from $B^0 \to c\bar{c}K^0$ decays, $\sin2\beta$ from loop-dominated charmless B^0 decays and measurements of $\cos2\beta$.

2. Analysis Technique

The angle β is extracted through measurements of time-dependent CP-asymmetries[4]. A_{CP} is defined as

$$A_{CP}(t) \equiv \frac{N(\overline{B}^0(t) \to f) - N(B^0(t) \to f)}{N(\overline{B}^0(t) \to f) + N(B^0(t) \to f)}$$
$$= S \sin(\Delta m_d t) - C \cos(\Delta m_d t), \qquad (1)$$

where $N(\overline{B}^0(t) \to f)$ is the number of $\overline{B}^0$ that decay into the CP-eigenstate f after a time t and Δm_d is the difference between the B mass eigenstates. The sinusoidal term describes interference between $B^0 - \overline{B}^0$ mixing and decay and the cosine term is the direct CP asymmetry.

The $B\overline{B}$ pair created in the $\Upsilon(4S)$ decay evolves coherently. Therefore, determining the flavor (B^0 or $\overline{B}^0$) of one B meson (B_{tag}) also determines the flavor of the other B at the time of the B_{tag} decay. The second B will continue to oscillate between flavor states. The effective tagging efficiency is $Q \equiv \sum_i \varepsilon_i (1 - 2w_i)^2 = (30.4 \pm 0.3)\,\%$, where the sum over i represents 6 mutually exclusive tagging categories, ε is the fraction of events in each category, and w is the fraction of incorrectly tagged events. The boosted center of mass allows for a measurement of the spatial separation of the B meson decay vertices to be converted into the proper time difference used in Eqn. 1.

An unbinned, extended maximum likelihood fit (MLF) is used to separate signal events from background and extract the CP parameters, S and C. Two kinematic variables from the $\Upsilon(4S)$ decay are calculated and used in the MLF. They are the energy-substituted mass $m_{\mathrm{ES}} = \sqrt{\frac{1}{4}s - \mathbf{p}_B^2}$ and energy difference $\Delta E = E_B - \frac{1}{2}\sqrt{s}$, where $(E_B, \mathbf{p}_B)$ is the B-meson 4-momentum vector, and all values are expressed in the $\Upsilon(4S)$ rest frame. Event shape variables are used to distinguish jet-like $q\bar{q}$ ($q = u, d, s, c$) events from nearly-isotropic B meson decays. The invariant mass and angular distribution (for vector mesons) are used to further separate signal from background events. Background from $B\overline{B}$ events tends to be small, and is included as a component in the MLF where needed. Fits to Monte Carlo simulations are used to determine signal and $B\overline{B}$ PDF shapes. Fits to on-peak data sidebands are used to determine the $q\bar{q}$ PDF shapes.

3. $\sin 2\beta$ from $B^0 \to c\bar{c}K^0$

The most precise measurement of β comes from $B^0 \to c\bar{c}K^0$ decays, where the b quark decays via the CKM-favored V_{cb} transition to a $c\bar{c}s$ final state.

In these decays, $S_{b \to c\bar{c}s} = -\eta_f \sin 2\beta$, where η_f is the CP eigenvalue of the final state[5]. A recent model-independent calculation finds an expected deviation of $S_{b \to c\bar{c}s}$ from $-\eta_f \sin 2\beta$ of 0.000 ± 0.017[6].

The measurement presented here combines the results for several such final states: $J/\psi K_S^0(\pi^+\pi^-)$, $J/\psi K_S^0(\pi^0\pi^0)$, $\psi(2S)K_S^0(\pi^+\pi^-)$, $\chi_{c1}K_S^0(\pi^+\pi^-)$, $\eta_c K_S^0(\pi^+\pi^-)$, $J/\psi K_L^0$ and $J/\psi K^{*0}(K_S^0\pi^0)$. The result of the combined MLF is

$$\sin 2\beta = 0.710 \pm 0.034 \pm 0.019, \tag{2}$$

where the first error is statistical and the second is systematic. This result, based on a data sample of 348 million $B\bar{B}$ pairs, is consistent with the current world average of 0.675 ± 0.026[7]. Thus, β is the most precisely measured CKM angle.

4. $\sin 2\beta$ from $b \to s$ Penguins

Decays of B^0 mesons to charmless hadronic final states such as $\eta' K^0$ proceed mostly via a single loop (penguin) amplitude. In the SM the penguin amplitude has approximately the same weak phase as the $b \to c\bar{c}s$ transition, but it is sensitive to the possible presence of new physics due to heavy particles in the loop[8]. If the only contribution to these decays were from the dominant SM penguin processes, $S_{b \to s} = -\eta_f \sin 2\beta$ as in the $b \to c\bar{c}s$ case. However, other decay processes can contribute as well. Pollution from non-leading order diagrams can cause $S_{b \to s} \neq S_{b \to c\bar{c}s}$, or $\Delta S \neq 0$, with $\Delta S \equiv S_{b \to s} - \sin 2\beta$. SM predictions and theoretical uncertainties for ΔS range from $\sim -0.05 - +0.20$ depending on the decay channel, [9,10,11,12] where the cleanest modes have $\Delta S \sim 0.01 \pm 0.01$. Any further deviation of ΔS from zero could be due to the presence of new physics in the loop, which is not possible in the $b \to c\bar{c}s$ case. Recent results from seven such $b \to s$ penguin-dominated decay channels are shown in Table 1.

As shown in Table 1, each measurement implies a negative value for ΔS. Moreover, the theoretical SM predictions for ΔS tend to be positive in nearly all cases. However, the uncertainties, both experimentally and theoretically, are still sufficiently large that no definite conclusions can be reached at this point. The single most precise measurement, that of $B^0 \to \eta' K^0$, now shows a deviation of 5.5σ from zero, which is the first observation of mixing-induced CP violation in a charmless B decay. The deviation from $\sin 2\beta$, however, is $\sim 1\sigma$. No individual channel represents a deviation from $\sin 2\beta \gtrsim 2\sigma$.

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5. Measurements of cos2β

The measurement of sin2β leaves a 4-fold ambiguity in the value of β. This ambiguity can be partially resolved with a measurement of cos2β. The final state $J/\psi K^{*0}(K_S^0\pi^0)$ contains both CP-even and CP-odd components. A full angular analysis of this final state allows for the extraction of cos2β with the result cos2$\beta > 0$ with 86% confidence based on a data sample of 88 million $B\overline{B}$ pairs[20].

Recently, two new technique have been used to deduce the sign of cos2β. Both B^0 and $\overline{B}^0$ mesons decay to the final state $D^{*+}D^{*-}K_S^0$. A potential interference effect of the decay proceeding through an intermediate resonance can be measured by dividing the B-decay Dalitz plot into regions with $m^2(D^{*+}K_S^0) > (<)m^2(D^{*-}K_S^0)$[21]. The resulting measurement concludes cos2$\beta > 0$ with 94% confidence[22] in agreement with the result from $J/\psi K^{*0}$. This result is based on a data sample of 230 million $B\overline{B}$ pairs.

A second new technique to determine the sign of cos2β utilizes the decay $B^0 \to D^0(\pi^+\pi^-K_S^0)h^0$, which can occur with or without $B^0 - \bar{B}^0$ mixing, where h^0 represents an η, η', π^0 or ω meson. Interference effects are visible across the D^0 Dalitz plot[23]. A full Dalitz plot fit measures sin2β = 0.45±0.35±0.05±0.07 and cos2β = 0.54±0.54±0.08±0.18, where the first uncertainty is statistical, the second is systematic and the third is theoretical, based on a data sample of 311 million $B\overline{B}$ pairs. This result shows a preference for a solution of β over $\pi/2 - \beta$ with 87% confidence[24], in good agreement with the previously reported measurements.

6. Conclusions

A variety of recent measurements of the CKM angle β are reported from *BABAR*. The direct measurement of sin2β from $b \to c\bar{c}s$ channels continues to be the most precise measurement. The sign of cos2β is now determined to be positive with at at least 86% confidence in three independent measurements. Several $b \to s$ penguin-dominated charmless final states continue to show a trend toward values of $S_{b\to s} < $ sin2β.

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Table 1. Time-dependent CP asymmetry parameter S and data sample size for $b \rightarrow s$ penguin-dominated charmless B decays. The first uncertainty is statistical and the second is systematic.

Mode	S	$\# B\overline{B}$ (millions)
$B^0 \rightarrow \eta' K^0$ [13]	$0.58 \pm 0.10 \pm 0.03$	384
$B^0 \rightarrow K^+ K^- K^0$ [14]	$0.66 \pm 0.12 \pm 0.06$	347
$B^0 \rightarrow \phi K^0$ [14]	$0.12 \pm 0.31 \pm 0.10$	347
$B^0 \rightarrow f_0 K^0$ [14]	$0.35 \pm 0.34 \pm 0.08$	347
$B^0 \rightarrow \omega K_S^0$ [15]	$0.62^{+0.25}_{-0.30} \pm 0.02$	347
$B^0 \rightarrow \rho^0 K_S^0$ [16]	$0.20 \pm 0.52 \pm 0.24$	227
$B^0 \rightarrow \pi^0 K_S^0$ [17]	$0.33 \pm 0.26 \pm 0.04$	348
$B^0 \rightarrow \pi^0 \pi^0 K_S^0$ [18]	$-0.72 \pm 0.71 \pm 0.08$	227
$B^0 \rightarrow K_S^0 K_S^0 K_S^0$ [19]	$0.66 \pm 0.26 \pm 0.08$	384