CP Asymmetries at *BABAR*

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Abstract. We present recent measurements of CP asymmetries in the B meson system, based on 92fb^{-1} collected with the *BABAR* detector at the PEP-II asymmetric-energy B factory at SLAC.

INTRODUCTION

CP violation was first observed in the K^0 system, almost 40 years ago [1]. The theoretical understanding of this phenomenon within the framework of the standard model (SM) led to the prediction of sizable CP violation in the B-meson system. In 2001, the *BABAR* and BELLE Collaborations announced the observation of CP violation in $B^0 \to J/\psi K_S$ decays [2, 3]. These results are in good agreement with the predictions of the standard model. Further constraints to the theory may come from the measurement of CP asymmetries in other B-decay channels. We present here several recent results of the measurement of CP asymmetries obtained by the *BABAR* Collaboration.

CP VIOLATION IN B-MESON DECAYS

In the standard model, CP violation arises from a single complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [4]. In the Wolfenstein parametrization of the CKM matrix [5], only V_{ub} and V_{td} are complex, and we define $\gamma \equiv \arg(V_{ub})$, $\beta \equiv \arg(V_{td})$ and $\alpha = \pi - \beta - \gamma$, the angles of the CKM unitarity triangle.

At asymmetric B factories, the B mesons are produced in pairs from the decay of the $\Upsilon(4S)$ resonance, and evolve coherently until the decay of one of the B mesons, B_{tag}. At that time, the flavor of the other B meson, B_{rec}, is opposite to that of B_{tag}. We write the decay rate distribution F_+ (F_-) for B_{rec} decays to the final state f when $B_{tag} = B^0(\bar{B}^0)$

$$F_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left[1 \pm S_f \sin(\Delta m_d \Delta t) \mp C_f \cos(\Delta m_d \Delta t)\right], \tag{1}$$

where τ is the mean B^0 lifetime and Δm_d is the mixing frequency due to the B eigenstates mass difference. The CP parameters S_f and C_f are defined as $S_f = 2\text{Im}\lambda_f/(1+|\lambda_f|^2)$ and $C_f = (1-|\lambda_f|^2)/(1+|\lambda_f|^2)$, where the convention-independent parameter $\lambda_f \equiv \eta_f \cdot q/p \cdot \bar{A}_{\bar{f}}/A_f$ [6]. In the definition of λ_f, η_f is the CP eigenvalue of f, q/p describes

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the $B^0-\bar{B}^0$ mixing, and A_f ($\bar{A}_{\bar{f}}$) is the $B^0 \to f$ ($\bar{B}^0 \to \bar{f}$) amplitude. The standard model predicts negligible CP violation in the mixing and in the decay, but a sizable CP violation in the interference between the mixing and the decay is expected (i.e. $\mathrm{Im}\lambda_{CP} \neq 0$).

In the processes of type $b \to c\bar{c}s$, $b \to c\bar{c}d$ and $b \to s\bar{s}s$, the dominant phase comes from mixing, and therefore the related decays are sensitive to the phase β. In addition to the phase β from mixing, the decays of type $b \to u\bar{u}d$ also depend on the phase γ from the $b \to u$ transition, and are therefore sensitive to the phase α.

Although direct CP violation is small in the standard model, it is expected to be larger in the B-meson system than it is in the kaon system (parameter ε'_K). We define the time-integrated CP asymmetry $\mathscr{A}_{CP} \equiv \left[\Gamma\left(\bar{B} \to \bar{f}\right) - \Gamma(B \to f)\right] / \left[\Gamma\left(\bar{B} \to \bar{f}\right) + \Gamma(B \to f)\right]$, which is sensitive to α and γ. Charmless B decays are of interest, because the penguin contribution can be large, allowing possible contributions from physics beyond the standard model. Unfortunately, the theoretical uncertainties are large due to the contribution of the strong phases in $\mathscr{A}_{CP}$.

DATA SAMPLE AND ANALYSIS TECHNIQUE

The results presented here are based on approximately $92\,\mathrm{fb}^{-1}$, corresponding to about 89 million $B\bar{B}$ pairs. The data were taken with the *BABAR* detector, located at the e^+e^- PEP-II asymmetric B factory at SLAC. The PEP-II collider runs at the $\Upsilon(4\mathrm{S})$ resonance (center of mass energy $\sqrt{s} = 10.58\,\mathrm{GeV}$). The $\Upsilon(4\mathrm{S})$ boost of $\beta\gamma = 0.56$ with respect to the laboratory frame allows time-dependent measurements of the B-meson decay rates. The *BABAR* detector is describe in details in Ref. [7].

Kinematic and events shape variables are used to separate signals from backgrounds, and the decay time difference Δt between the two B mesons produced in the $\Upsilon(4\mathrm{S})$ decay is used for the time-dependent measurements.

The kinematic variables are the energy difference $\Delta E = E_B^\star - \sqrt{s}/2$, the energy substituted mass $m_{ES} = \sqrt{(s/2 + \vec{p}_0 \cdot \vec{p}_B)^2/E_0^2 - |\vec{p}_B|}$, and the mass and decay angle of the resonances involved in the B-meson decay under study. In the above definitions, $(E_0, \vec{p}_0)$ and $(E_B, \vec{p}_B)$ are the 4-vectors of the initial $\Upsilon(4\mathrm{S})$ and B candidate, respectively, and $E_B^\star$ is the B candidate energy measured in the $\Upsilon(4\mathrm{S})$ frame.

The dominant background arises from the abundant $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) events. The topology of these events is jetty relative to the spherical $\Upsilon(4\mathrm{S}) \to \mathrm{B\bar{B}}$ events. This difference is used in constructing a set of event-shape variables.

For the time-dependent measurements, both B_{rec} and B_{tag} are reconstructed and Δt is calculated from the distance Δz between their decay vertices. The value of Δz is typically 260μm, measured with a resolution of 180μm. From the partial reconstruction of B_{tag}, we also determine its flavor at the time of the decay.

For each decay mode, the discriminating variables are used in a maximum likelihood (ML) fit, from which the signal and background yields, the charge asymmetries, $\mathscr{A}_{CP}$, and the time-dependent asymmetries are extracted. The ML fit is extensively tested and validated using Monte-Carlo simulated and real data control samples. A detailed description of the analysis technique can be found in Ref. [8].

TEST OF CP, T AND CPT CONSERVATION IN $B^0-\bar{B}^0$ MIXING

We tested the predicted (SM) very small lifetime difference $\Delta\Gamma \equiv \Gamma_H - \Gamma_L$ between the B mass eigenstates (B_H and B_L), the negligible T violation and the absence of CPT violation in $B^0-\bar{B}^0$ mixing. From a simultaneous time-dependent fit to the CP and flavor eigenstate samples, we measure $\Delta\Gamma/\Gamma$, $|q/p|$, the CPT-sensitive z parameter, and λ_{CP} [9]:

$$\begin{aligned}
\mathrm{sign}(\mathrm{Re}\lambda_{CP}) &= -0.008 \pm 0.037 \pm 0.018 \quad [-0.084, 0.068] \\
|q/p| &= 1.029 \pm 0.013 \pm 0.011 \quad [\ \ 1.001, 1.057] \\
(\mathrm{Re}\lambda_{CP}/\left|\lambda_{CP}\right|)\mathrm{Re}z &= 0.014 \pm 0.035 \pm 0.034 \quad [-0.072, 0.101] \\
\mathrm{Im}z &= 0.038 \pm 0.029 \pm 0.025 \quad [-0.028, 0.104]
\end{aligned}$$

where the first (second) uncertainty is statistical (systematic). The square brackets give the 90% confidence-level intervals. The results are compatible with the SM predictions.

MEASUREMENTS OF THE PHASE β

As a reminder, we give here the results for the measurement of $\sin 2\beta$ obtained from the theoretically well understood and experimentally clean B-meson decays involving $b \to c\bar{c}s$ transitions (golden channels). From a sample of 2641 events, we obtain [10]

$$\sin 2\beta = 0.741 \pm 0.067 \pm 0.034 \qquad \text{and} \qquad |\lambda| = 0.948 \pm 0.051 \pm 0.030,$$

compatible with the SM expectation of $|\lambda| \approx 1$. The above value of $\sin 2\beta$ is taken as a reference in the following discussion.

The cleanest example of a $b \to s\bar{s}s$ penguin dominated transitions comes from the $B \to \phi K$ decays. The value of $S_{\phi K_S}$ is expected to be a clean measurement of $\sin 2\beta$. Any significant deviation from $\sin 2\beta$ would be a sign of physics beyond the standard model. With 50 ± 9 $B^0 \to \phi K_S$ and about 170 $B^+ \to \phi K^+$ signal events, we measure [11]

$$\begin{aligned}
\mathscr{A}_{CP}(B^+ \to \phi K^+) &= (3.9 \pm 8.6 \pm 1.1)\% \\
S_{\phi K_S} &= -0.18 \pm 0.51 \pm 0.07 \\
C_{\phi K_S} &= -0.80 \pm 0.38 \pm 0.12
\end{aligned}$$

$S_{\phi K_S}$ shows a two standard deviation discrepancy with the value of $\sin 2\beta$ obtained in the $b \to c\bar{c}s$ channels. Although not statistically significant, this may be a hint for non-standard model physics.

Similarly to $B \to \phi K$, the $B \to \eta' K$ decays are dominated by $b \to s\bar{s}s$ penguin transitions. However, due to the $u\bar{u}$ and $d\bar{d}$ content of the η' meson, a contamination from tree processes may exist, making the time-dependent asymmetry more difficult to interpret. On the other hand, the large branching fraction of this decay allows a more precise measurement of the CP parameters.

From ≈ 800 $B^+ \to \eta' K^+$ and ≈ 200 $B^0 \to \eta' K_S$ signal events reconstructed in two different decays of the η' ($\eta' \to \eta\pi^+\pi^-$ and $\eta' \to \rho^0\gamma$), we obtain [12]

$$\begin{aligned}
\mathscr{A}_{CP}(B^+ \to \eta' K^+) &= (3.7 \pm 4.5 \pm 1.1)\% \\
S_{\eta' K_S} &= 0.02 \pm 0.34 \pm 0.03 \\
C_{\eta' K_S} &= 0.10 \pm 0.22 \pm 0.04
\end{aligned}$$

$S_{\eta' K_S}$ shows a two standard deviation discrepancy with the expected value of $\sin 2\beta$, but the theoretical uncertainties are large, and therefore no firm conclusion can be drawn.

We also obtained preliminary CP results for the decay modes $B^0 \to J/\psi \pi^0$ and $B^0 \to D^{\star\pm} D^{\mp}$. These decays proceed through a $b \to c\bar{c}d$ transition, with contributions from both tree and penguin amplitudes. However, we expect $S_{J/\psi \pi^0} = S_{D^{\star +} D^-} = S_{D^{\star -} D^+} = -\sin 2\beta$ if the penguin amplitude is negligible. From samples of 40 ± 7 $B^0 \to J/\psi \pi^0$ and 113 ± 13 $B^0 \to D^{\star\pm} D^{\mp}$ signal events, we obtain [13, 14]

$$
\begin{array}{rclcrcl}
S_{J/\psi \pi^0} & = & 0.05 \pm 0.49 \pm 0.16 & & C_{J/\psi \pi^0} & = & 0.38 \pm 0.41 \pm 0.09 \\
S_{D^{\star +} D^-} & = & -0.82 \pm 0.75 \pm 0.14 & & C_{D^{\star +} D^-} & = & -0.47 \pm 0.40 \pm 0.12 \\
S_{D^{\star -} D^+} & = & -0.24 \pm 0.69 \pm 0.12 & & C_{D^{\star -} D^+} & = & -0.22 \pm 0.37 \pm 0.10
\end{array}
$$

Increased statistics will be necessary before these decay modes can be used for constraining the standard model.

MEASUREMENTS OF THE PHASE α

The $B^0 \to \pi^+\pi^-$ decay is dominated by the tree amplitude, but it is known from the large $B^0 \to K^+\pi^-$ branching fraction that the penguin amplitude contribution is large. As a consequence, the measured value of $\sin 2\alpha_{\text{eff}} \equiv S_{\pi^+\pi^-}$ is not expected to be equal to $\sin 2\alpha$. But it has been suggested to use an isospin analysis of the $B \to \pi\pi$ decay modes to extract the value of α from α_{eff} [15]. From our measurements of the $B \to \pi\pi$ branching fractions [16], we set the limit $\left|\alpha - \alpha_{\text{eff}}\right| < 51^\circ$. From a simultaneous fit of both $B^0 \to \pi^+\pi^-$ and $B^0 \to K^+\pi^-$ decays, we obtain [17]

$$
\begin{array}{rcl}
\mathscr{A}_{CP}(B^0 \to K^+\pi^-) & = & (-10.2 \pm 5.0 \pm 1.6)\% \\
S_{\pi^+\pi^-} & = & 0.02 \pm 0.34 \pm 0.05 \\
C_{\pi^+\pi^-} & = & -0.30 \pm 0.25 \pm 0.04
\end{array}
$$

The result for $S_{\pi^+\pi^-}$ is compatible with the naively expected value of $\alpha_{\text{eff}} \approx 90^\circ$.

The phase α may also be extracted from a dalitz plot analysis of the decay $B \to \pi^+\pi^-\pi^0$. This channel has the advantage of a larger branching fraction ($\approx 4\times$) and a smaller contribution from penguin amplitude than the $B^0 \to \pi^+\pi^-$ channel. We performed this challenging analysis as a simpler pseudo two-body analysis, selecting a $\rho^\pm \to \pi^\pm\pi^0$ candidate recoiling against a $\pi^\mp$. From ≈ 430 $B^0 \to \rho^+\pi^-$ and ≈ 120 $B^0 \to \rho^+ K^-$ signal events, we measure [18]

$$
\begin{array}{rcl}
\mathscr{A}_{CP}(B^0 \to \rho^+ K^-) & = & (28 \pm 17 \pm 8)\% \\
\mathscr{A}_{CP}(B^0 \to \rho^+ \pi^-) & = & (-18 \pm 8 \pm 3)\% \\
S_{\rho^\pm \pi^\mp} & = & 0.19 \pm 0.24 \pm 0.03 \\
C_{\rho^\pm \pi^\mp} & = & 0.36 \pm 0.18 \pm 0.04
\end{array}
$$

The over two standard deviation discrepancy of $\mathscr{A}_{CP}(B^0 \to \rho^+\pi^-)$ from the no-direct CP violation hypothesis is not significant to allow any useful conclusion.

SEARCHES FOR DIRECT CP VIOLATION

Finally, we have searched for direct CP violation in 19 different charmless decay modes of the B mesons, including some of the results presented above. Only three of these modes show a deviation larger than two standard deviations from no asymmetry: $\mathscr{A}_{CP}(B^0 \to \rho^+\pi^-) = (-18 \pm 8 \pm 3)\%$, $\mathscr{A}_{CP}(B^+ \to \eta\pi^+) = (-51^{+20}_{-18} \pm 1)\%$ [19] and $C_{\phi K_S} = -0.80 \pm 0.38 \pm 0.12$. These deviations are compatible with the expectation of statistical fluctuations. However, it should be noted that theoretical calculations predict large asymmetries for both $\mathscr{A}_{CP}(B^0 \to \rho^+\pi^-)$ and $\mathscr{A}_{CP}(B^+ \to \eta\pi^+)$ [see references in [18] and [19]]. Increased statistics will help clarify the situation.

CONCLUSION

Besides the well measured $\sin 2\beta$ in the golden channels, the *BABAR* Collaboration has obtained preliminary results in several other decay modes sensitive to the CKM phases α and β. Some results show interesting deviations from the expected values, but more statistics will be required before any conclusion can be drawn. Pursuing the goal of better accuracy, the *BABAR* experiment is expecting to accumulate over $500\,\text{fb}^{-1}$ by 2006.

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