CP Violation measurements in $B \to$ charm decays at $BABAR$.

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Abstract
This article summarises measurements of time-dependent $CP$ asymmetries in decays of neutral $B$ mesons to charm final states using data collected by the $BABAR$ detector at the PEP-II asymmetric-energy $B$ factory. All results are preliminary unless otherwise stated.

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1 Introduction

The Standard Model (SM) of particle physics describes CP violation as a consequence of a complex phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. In this framework, measurements of CP asymmetries in the proper-time distribution of neutral B decays to CP eigenstates containing a charmonium and $K^0$ meson provide a direct measurement of $\sin 2\beta$ [2]. The unitarity triangle angle $\beta$ is $\arg \left[-V_{c d}V_{c b}^*/V_{d c}V_{d b}\right]$ where the $V_{i j}$ are CKM matrix elements.

The BaBar detector [3] is located at the SLAC PEP-II $e^+e^-$ asymmetric energy B-factory. Its program includes the measurement of $\beta$ through the measurement of time-dependent CP-asymmetries, $A_{CP}$. At the $T(4S)$ resonance, $A_{CP}$ is extracted from the distribution of the difference of the proper decay times, $t \equiv t_{CP} - t_{tag}$, where $t_{CP}$ refers to the decay time of the signal $B$ meson ($B_{CP}$) and $t_{tag}$ refers to the decay time of the other $B$ meson in the event ($B_{tag}$). The decay products of $B_{tag}$ are used to identify its flavor at its decay time.

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

where $N(B^0(t) \rightarrow f)$ is the number of $B^0$ that decay into the $CP$-eigenstate $f$ after a time $t$ and $\Delta m_d$ is the difference between the $B$ mass eigenstates. The sinusoidal term describes interference between mixing and decay and the cosine term is the direct $CP$ asymmetry. $S$ and $C$ are functions of the parameter $\lambda$ and are defined as follows:

$$S = \frac{2 \cdot \text{Im} |\lambda|}{1 + |\lambda|^2},$$
$$C = \frac{1 - |\lambda|^2}{1 + |\lambda|^2},$$

$$\lambda = \frac{q}{p} \cdot \frac{A(B^0(t) \rightarrow \bar{f})}{A(B^0(t) \rightarrow f)}.$$ (1)

In Eq. (1) $A(B^0(t) \rightarrow \bar{f}) (A(B^0(t) \rightarrow f))$ is the decay amplitude of $B^0$ ($B^0$) to the final state $\bar{f}$ ($f$).

The physical states (solutions of the complex effective Hamiltonian for the $B^0$-$\bar{B}^0$ system) can be written in terms of the parameters $p$, $q$ and $z$ [4]:

$$|B_L\rangle = p\sqrt{1-z}|B^0\rangle + q\sqrt{1+z}|\bar{B}^0\rangle,$$
$$|B_H\rangle = p\sqrt{1+z}|B^0\rangle - q\sqrt{1-z}|\bar{B}^0\rangle,$$

where $H$ and $L$ denote the Heavy and Light mass eigenstates. Under CPT symmetry, the complex parameter $z$ vanishes. $T$ invariance implies $|q/p| = 1$ and $CP$ invariance requires both $|q/p| = 1$ and $z = 0$. In this article the current status of measurements of CP violation in $B \rightarrow$ charm decays and studies of searches for $T$, CPT and $CP$ violation in $B^0$-$\bar{B}^0$ mixing are presented. All results are preliminary unless otherwise stated.

2 $b \rightarrow c\bar{c}s$ decay modes

The determination of $\beta$ from $b \rightarrow c\bar{c}s$ decay modes currently provides the most stringent constraint on the unitarity triangle. For these decay modes, the $CP$ violation parameters in Eq. (1) are $S_{b\rightarrow c\bar{c}s} =$
$-\eta_f \sin 2\beta$ and $S_{b\to c\bar{s}} = 0$, where $\eta_f$ is $-1$ for $(c\bar{s})K^0_S$ decays (e.g. $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_c K^0_S$, $\eta_c K^0_S$ [5]) and $\eta_f$ is $+1$ for the $(\bar{c}\bar{s})K^0_S$ (e.g. $J/\psi K^0_L$) state. We use the value $\eta_f = 0.504 \pm 0.033$ for the $J/\psi K^{\pm}(K^{*0} \to K^0_S \pi^0)$ final state since it can be both $CP$ even and $CP$ odd due to the presence of even and odd orbital angular momentum contributions [6]. These modes have been used to measure $\sin 2\beta$ using 348 $M_B\bar{B}$ pairs [7], where an improved event reconstruction has been applied to the complete dataset, and a new $\eta_c K^0_S$ event selection has been developed based on the Dalitz structure of the $\eta_c \to K^0_S K^+\pi^-$ decay. We measure [8]

$$\sin 2\beta = 0.715 \pm 0.034 \pm 0.019,$$

$$|\lambda| = 0.932 \pm 0.026 \pm 0.017$$

which is in agreement with SM expectations. Figure 1 shows the $\Delta t$ distributions and asymmetries in yields between $B^0$ tags and $B^\ast 0$ tags for the $\eta_f = -1$ and $\eta_f = +1$ samples as a function of $\Delta t$, overlaid with the projection of the likelihood fit result.

**3 cos2$\beta$ measurements**

The analysis of $b \to c\bar{s}$ decay modes imposes a constraint on $\sin 2\beta$ only, leading to a four-fold ambiguity in the determination of $\beta$. This ambiguity can lead possible new physics undetected even with very high precision measurements of $\sin 2\beta$. Additional constraints are obtained from the ambiguity-free measurement of $\cos 2\beta$ using the angular and time-dependent asymmetry in $B^0 \to J/\psi K^*$ decays and the time-dependent Dalitz plot analyses of $B^0 \to D^{\ast 0} h^0$ and $B^0 \to D^{\ast +} D^{\ast -} K^0_S$. The $B^0 \to J/\psi K^*$ analysis is published in Ref. [9].

A model-independent measurement of $\cos 2\beta$ in $B^0 \to D^{\ast 0} h^0$ decays has been made using a time-dependent Dalitz plot analysis of $D^0 \to K^0_S \pi^+ \pi^-$, where $h^0$ is a light neutral meson such as $\pi^0$, $\eta$, $\eta'$ or $\omega$ [10]. The strong phase variation on the $D^0 \to K^0_S \pi^+ \pi^-$ Dalitz plot allows access to the angle $\beta$ with only a two-fold ambiguity ($\beta + \pi$) [11]. Using 311 $M_B\bar{B}$ pairs, the following values of the $CP$ asymmetry parameters are extracted:

$$\cos 2\beta = 0.54 \pm 0.54 \pm 0.08 \pm 0.18,$$

$$\sin 2\beta = 0.45 \pm 0.36 \pm 0.05 \pm 0.07,$$

$$|\lambda| = 0.975^{+0.093}_{-0.085} \pm 0.012 \pm 0.002,$$

where in addition to the statistical and systematic errors, there are also uncertainties from the signal Dalitz model. Assuming that $\sin 2\beta$ takes the same value as the $b \to c\bar{s}$ decay average in Ref. [12] and that there is no $CP$ violation in $B^0\bar{B}$ mixing, a parameterised Monte Carlo method based on the observed data finds that these measurements favour the solution of $\beta = 22^\circ$ over $68^\circ$ at an 87% confidence level.

A study of the decay $B^0 \to D^{\ast +} D^{\ast -} K^0_S$ has been made using 230 $M_B\bar{B}$ pairs [13]. The branching fraction $B(B^0 \to D^{\ast +} D^{\ast -} K^0_S) = (4.4 \pm 0.4 \pm 0.7) \times 10^{-3}$ has been measured and evidence found for the decay $B^0 \to D^{\ast +} D_s^{\ast -}(2536) K^0_S$ with a 4.6σ statistical significance. The time-dependent decay rate asymmetry of $B^0 \to D^{\ast +} D^{\ast -} K^0_S$ can be written in terms of the parameters $J_0$, $J_{s1}$, $J_{s2}$ and $J_c$ which are integrals over the half Dalitz space of the decay amplitudes of $B^0 \to D^{\ast +} D^{\ast -} K^0_S$ and $B^0 \to D^{\ast +} D^{\ast -} K^0_S$. The fits to the data yield:

$$J_c \over J_0 = 0.76 \pm 0.18 \pm 0.07,$$
Figure 1: a) Number of $\eta_f = -1$ candidates ($J/\psi K_s^0$, $\psi(2S) K_s^0$, $\chi_c1 K_s^0$, and $\eta_c K_s^0$) in the signal region with a $B^0$ tag $N_{B^0}$ and with a $\bar{B}^0$ tag $N_{\bar{B}^0}$, and b) the raw asymmetry $(N_{B^0} - N_{\bar{B}^0})/(N_{B^0} + N_{\bar{B}^0})$, as functions of $\Delta t$. Figs. c) and d) are the corresponding plots for the $\eta_f = +1$ mode $J/\psi K_{L}^0$. The solid (dashed) curves represent the fit projections in $\Delta t$ for $B^0$ ($\bar{B}^0$) tags. The shaded regions represent the estimated background contributions.
The measured value of $J_c/J_0$ is significantly different from zero, which, according to Ref. [14], may indicate that there is a sizeable broad resonant contribution to the decay $B^0 \rightarrow D^{*+} D^{*-} K_S^0$ from an unknown $D_{s1}^+$ state with an unknown width. Under this assumption then the measured value of $2J_{s2}/J_0$ implies that the sign of $\cos 2\beta$ is preferred to be positive at a 94% confidence level.

Figure 2 illustrates the combined constraint on $\beta$ in the $\rho$-$\eta$ plane from the Belle and BABAR $b \rightarrow c\bar{s}s$, $B^0 \rightarrow J/\psi K^*$, $B^0 \rightarrow D^{*0} h^0$ and $B^0 \rightarrow D^{*+} D^{*-} K_S^0$ analyses [12].

Figure 2: Constraint on $\beta$ in the $\rho$-$\eta$ plane, obtained from the analysis of $b \rightarrow c\bar{s}s$ decays, the angular analysis of $B^0 \rightarrow J/\psi K^*$ and the time-dependent Dalitz plot analyses of $B^0 \rightarrow D^{*0} h^0$ and $B^0 \rightarrow D^{*+} D^{*-} K_S^0$. The hatched area corresponding to the solution $\beta = 68.8 \pm 1.0^\circ$ where $\cos 2\beta$ is negative, is strongly disfavoured.

4 Studies of $T$, $CPT$ and $CP$ violation in $B^0$-$\bar{B}^0$ mixing.

Inclusive dilepton events, where both $B$ mesons decay semileptonically represent 4% of all $\Upsilon(4S) \rightarrow B^0\bar{B}^0$ decays and provide a very large sample with which to study $T$, $CPT$ and $CP$ violation in $B^0$-$\bar{B}^0$ mixing. The same-sign dilepton asymmetry $A_{T/CP}$ between the two oscillation probabilities $P(\bar{B}^0 \rightarrow B^0)$ and $P(B^0 \rightarrow \bar{B}^0)$ is sensitive to $|q/p|$ and probes both $T$ and $CP$ symmetries. The
opposite-sign dilepton asymmetry $A_{T/CPT}$ compares the probabilities $P(B^0 \rightarrow B^0)$ and $P(\overline{B}^0 \rightarrow \overline{B}^0)$ and probes $CPT$ and $CP$ violation. It is sensitive to the product $\Delta\Gamma \cdot \text{Re} \, z$ where $\Delta\Gamma$ is the difference between the decay rates of the neutral $B$ mass eigenstates. The result published in Ref. [15] uses a sample of 232 $M\overline{B}\overline{B}$ pairs to measure the $T$ and $CP$ violation parameter

$$|q/p| - 1 = (-0.8 \pm 2.7 \pm 1.9) \times 10^{-3}$$

and the $CPT$ and $CP$ parameters

$$\text{Im} \, z = (-13.9 \pm 7.3 \pm 3.2) \times 10^{-3},$$
$$\Delta\Gamma \cdot \text{Re} \, z = (-7.1 \pm 3.9 \pm 2.0) \times 10^{-3} \text{ ps}^{-1}.$$  

The statistical correlation between the measurements of $\text{Im} \, z$ and $\Delta\Gamma \cdot \text{Re} \, z$ is 76%. A search is then made for time-dependent variations in the complex $CPT$ parameter $z = z_0 + z_1 \cos (\Omega t + \phi)$ where $\Omega$ is the Earth’s sidereal frequency and $t$ is sidereal time [16]. We measure:

$$\text{Im} \, z_0 = (-14.1 \pm 7.3 \pm 2.4) \times 10^{-3},$$
$$\Delta\Gamma \cdot \text{Re} \, z_0 = (-7.2 \pm 4.1 \pm 2.1) \times 10^{-3} \text{ ps}^{-1},$$
$$\text{Im} \, z_1 = (-24.0 \pm 10.7 \pm 5.9) \times 10^{-3},$$
$$\Delta\Gamma \cdot \text{Re} \, z_1 = (-18.8 \pm 5.5 \pm 4.0) \times 10^{-3} \text{ ps}^{-1}.$$  

The statistical correlation between the measurements of $\text{Im} \, z_0$ and $\Delta\Gamma \cdot \text{Re} \, z_0$ is 76%; and between $\text{Im} \, z_1$ and $\Delta\Gamma \cdot \text{Re} \, z_1$ is 79%. Figure 3 shows confidence level contours for the parameters $\text{Im} \, z_1$ and $\Delta\Gamma \cdot \text{Re} \, z_1$ including both statistical and systematic errors. A significance of 2.2$\sigma$ is found for periodic variations in the $CPT$ violation parameter $z$ at the sidereal frequency, characteristic of Lorentz violation.

![Figure 3](image)

**Figure 3**: Confidence level contours for the parameters $\text{Im} \, z_1$ and $\Delta\Gamma \cdot \text{Re} \, z_1$. The line contours indicate 1$\sigma$, 2$\sigma$, and 3$\sigma$ significance. The star at $\text{Im} \, z_1 = \Delta\Gamma \cdot \text{Re} \, z_1 = 0$ indicates the condition for no sidereal-time dependence in $z$.

A measurement of the parameter $|q/p|$ has also been made using the partial reconstruction of one of the $B$ mesons in the semileptonic channel $D^{*-} \ell^+ \nu_\ell$, where only the hard lepton and the soft
pion from the $D^* \to D^0 \pi^-$ decay are reconstructed \cite{17}. A data sample of 220 $M_B \overline{M}_B$ pairs are used. We measure

$$|q/p| - 1 = (6.5 \pm 3.4 \pm 2.0) \times 10^{-3}$$

which is consistent with SM expectations.

5 Conclusion

An improved measurement of $\sin^2 \beta$ has been made using $B^0 \to \text{charmonium} + K^0$ decays. This is consistent with SM expectations and continues to provide the most stringent constraint on the unitarity triangle. Analysis of the $b \to c \bar{s}s$, $B^0 \to J/\psi K^*$, $B^0 \to D^{*0} h^0$ and $B^0 \to D^{*+} D^{*-} K_S^0$ modes indicate that the solution $\beta = 21.1 \pm 1.0^\circ$ is strongly preferred. The measurements of $|q/p|$ from analyses of inclusive dilepton and $D^{*-} \ell^+\nu_\ell$ events are in agreement with SM predictions.

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