

BaBar: $\sin 2\beta$ with charm

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We present measurements of time-dependent CP asymmetries of neutral B decays to several charm and charmonium final states. Data have been collected with the *BABAR* detector at the PEP-II storage ring at the Stanford Linear Accelerator Center. In the absence of penguin contribution, the Standard Model predicts the time-dependent CP asymmetry parameters S and C are to be $-\eta_{CP} \sin(2\beta)$ and 0, respectively.

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1. Introduction and time-dependent CP asymmetry measurement principle

Charge conjugation-parity (CP) violation is described in the Standard Model (SM) by a single complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [1]. CP violation has been established in the B meson system by the BABAR [2] and Belle [3] collaborations which have precisely measured the parameter $\sin(2\beta)$, where $\beta = \arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*]$ and V_{ij} are the CKM matrix elements. For a B meson from a $Y(4S) \rightarrow B^0\bar{B}^0$ decay, the SM predicts the decay rate $f_+(f_-)$ when the other B meson B_{tag} has been determined to be B^0 (\bar{B}^0):

$$f_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[1 \pm \frac{2\text{Im}\lambda}{1+|\lambda|^2} \sin(\Delta m\Delta t) \mp \frac{1-|\lambda|^2}{1+|\lambda|^2} \cos(\Delta m\Delta t) \right] \quad (1.1)$$

Here, Δt is the difference between the proper decay times of the reconstructed B meson B_{rec} and B_{tag} , τ_{B^0} is the B^0 lifetime, Δm is the mass difference between the B^0 mass eigenstates B_H and B_L . The decay width difference $\Delta\Gamma$ between the B^0 mass eigenstates has been assumed to be zero. The complex parameter λ is given by: $\lambda = [q/p][\bar{A}_f/A_f]$. q and p define the transformation basis between the mass eigenstates and the weak eigenstates $|B_{H/L}\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle$, and A_f and \bar{A}_f are the decay amplitude for $B^0 \rightarrow f$ and $\bar{B}^0 \rightarrow f$ respectively. The sine term describes the interference between decay with mixing and decay without mixing. The cosine term mainly arises from direct CP violation as CP violation in mixing is predicted to be small in the SM. Experimentally, the following time-dependent CP asymmetry is measured, where S and C are fitted to the data:

$$A_{CP}(t) = \frac{N(\bar{B}^0 \rightarrow f_{CP}) - N(B^0 \rightarrow f_{CP})}{N(\bar{B}^0 \rightarrow f_{CP}) + N(B^0 \rightarrow f_{CP})} = S \sin(\Delta mt) - C \cos(\Delta mt) \quad (1.2)$$

2. Measurement of CP asymmetry in $B^0 \rightarrow (c^-c)K^{0(*)}$ decays

The following CP modes have been used: $J/\psi K_S^0$, $\psi(2S) K_S^0$, $\chi_{c1} K_S^0$, $\eta_c K_S^0$ with CP eigenvalue $\eta_{CP} = -1$, $J/\psi K_L^0$ with CP eigenvalue $\eta_{CP} = +1$, and $J/\psi K^{*0}$. Depending on the value of the angular momentum, the $J/\psi K^{*0}$ final state can be CP -even ($L=0,2$) or CP -odd ($L=1$). The measurement asymmetry is reduced by a factor $|1 - 2R_{\perp}|$, where $R_{\perp} = 0.230 \pm 0.015 \pm 0.004$ [4] is the fraction of CP -odd measured in a time-integrated analysis of $J/\psi K^{*0}(K^+\pi^-)$. After acceptance corrections, we obtain an effective eigenvalue $\eta_{CP} = -0.51 \pm 0.04$.

We fully reconstruct a decay B_{rec} to the final states listed above. The rest of the event is assigned to the other B meson B_{tag} and is used in a neural network to determine the B_{tag} flavor and therefore the flavor of the B_{rec} meson at $\Delta t = 0$. There are six tagging categories. The time interval Δt is obtained from the measurement of the reconstruction of the decay vertices of B_{rec} and B_{tag} . Flavor tagging and Δt resolution are calibrated using a large sample of B^0 decays to flavor eigenstates (B_{flav}). The beam-energy substituted mass $m_{ES} = \sqrt{(E_{beam}^{cm})^2 - (p_B^{cm})^2}$ (for all modes except for $J/\psi K_L^0$) or the difference ΔE between the candidate center-of-mass energy and E_{beam}^{cm} ($J/\psi K_L^0$ only) is used to estimate the sample composition.

We determine $\sin(2\beta)$ in a data sample of approximately $227 \times 10^6 Y(4S) \rightarrow B\bar{B}$ decays with a simultaneous maximum likelihood fit to the Δt distributions of both the B_{rec} and B_{flav} samples. There are in total 65 parameters in the fit. Figure 1 shows the Δt distributions and raw asymmetries for both the CP eigenvalues $\eta_{CP} = -1$ and $+1$. The fit yields the result [5]:

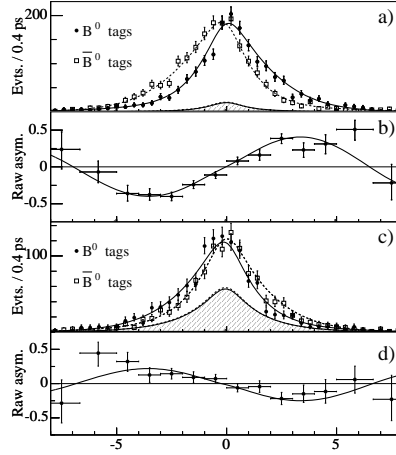


Figure 1: a) Number of $\eta_{CP} = -1$ candidates ($J/\psi K_S^0$, $\psi(2S) K_S^0$, $\chi_{c1} K_S^0$ and $\eta_c K_S^0$) in the signal region with a B^0 tag N_{B^0} and with a \bar{B}^0 tag $N_{\bar{B}^0}$, and b) the raw asymmetry A_{CP}^{raw} , as a function of Δt . Figures c) and d) are the corresponding plots for the $\eta_{CP} = +1$ mode $J/\psi K_L^0$. The solid (dashed) curves represent the fit projections in Δt for B^0 (\bar{B}^0) tags. The shaded area regions represent the estimated background contributions.

$$\sin(2\beta) = 0.722 \pm 0.040(stat) \pm 0.023(syst). \quad (2.1)$$

3. Measurement of CP asymmetry in $B^0 \rightarrow J/\psi \pi^0$ decays

The $B^0 \rightarrow J/\psi \pi^0$ decay is a Cabibbo and color-suppressed $b \rightarrow c\bar{c}d$ transition. In the absence of loop contributions, the SM predicts the sine coefficient of the time-dependent CP asymmetry to be $S = -\sin(2\beta)$ and the cosine coefficient C to be zero. The weak phase of $b \rightarrow c\bar{c}d$ tree amplitude is the same as for the $b \rightarrow c\bar{c}s$ transitions (measured through $B \rightarrow (c\bar{c}K^{0(*)})$ modes), but is different from the penguin amplitudes. Therefore if penguin amplitudes contribute significantly to the $B^0 \rightarrow J/\psi \pi^0$ decay, values of S and C will differ from $-\sin(2\beta)$ and zero [6].

The signal is isolated using the two kinematic variables m_{ES} and ΔE . A Fisher discriminant F based on kinematic and topological variables has been used to improve background rejection. The values of the signal yield, S and C are simultaneously extracted from a maximum likelihood fit to the m_{ES} , ΔE , F and Δt distributions. From a data sample of approximately $232 \times 10^6 \Upsilon(4S) \rightarrow B\bar{B}$ decays, the fit returns $109 \pm 12(stat)$ signal events and the CP parameters [7]:

$$S = -0.68 \pm 0.30(stat) \pm 0.04(syst) \quad C = -0.21 \pm 0.26(stat) \pm 0.09(syst) \quad (3.1)$$

These values are consistent with the SM expectations for a tree-dominated $b \rightarrow c\bar{c}d$ transition with $S = -\sin(2\beta)$ and $C = 0$.

4. Measurement of CP asymmetry in open-charm modes

We have measured time-dependent CP asymmetries in $B^0 \rightarrow D^{*+}D^{*-}$ and $B^0 \rightarrow D^{(*)\pm}D^\mp$ In a data sample of approximately $232 \times 10^6 \Upsilon(4S) \rightarrow B\bar{B}$ decays. These color-allowed decays are

dominated by the $b \rightarrow c\bar{c}d$ transition. Within the SM, the CP asymmetries are related to $\sin(2\beta)$, assuming the penguin contributions are neglected. Penguin corrections have been estimated to be at the level of a few percents [8].

The $B^0 \rightarrow D^{*+}D^{*-}$ decay occurs through both CP -even and CP -odd transitions. The fraction of CP -odd R_{\perp} has been determined from a time-integrated one-dimensional angular analysis which yields: $R_{\perp} = 0.125 \pm 0.044(stat) \pm 0.007(syst)$.

Signal yields and CP parameters are extracted using simultaneous maximum likelihood fits of B_{rec} and B_{flav} samples on Δt distributions and m_{ES} , and $\cos(\theta_{tr})$ for the $B^0 \rightarrow D^{*+}D^{*-}$ decay mode (θ_{tr} in the transversity basis is the polar angle of the slow pion from the D^{*+} defined in the D^{*+} rest frame, where the opposite direction of flight of the D^{*-} is chosen as the x -axis, and the z -axis is defined as the normal to the D^{*-} decay plane). For the $B^0 \rightarrow D^{*+}D^{*-}$, only CP -even parameters results are shown (the CP -odd parameters, with much larger statistical errors, are found to be consistent with the CP -even results). The signal yields are found to be $391 \pm 28(stat)$, $126 \pm 16(stat)$, $145 \pm 16(stat)$, and $54 \pm 11(stat)$ events for the $B^0 \rightarrow D^{*+}D^{*-}$, $B^0 \rightarrow D^{*-}D^+$, $B^0 \rightarrow D^{*+}D^-$, and $B^0 \rightarrow D^+D^-$ decay modes, respectively. The results for the CP parameters are [9]:

$$S_{D^{*+}D^{*-}} = -0.75 \pm 0.25(stat) \pm 0.03(syst) \quad C_{D^{*+}D^{*-}} = 0.06 \pm 0.17(stat) \pm 0.03(syst) \quad (4.1)$$

$$S_{D^{*+}D^-} = -0.54 \pm 0.35(stat) \pm 0.07(syst) \quad C_{D^{*+}D^-} = 0.09 \pm 0.25(stat) \pm 0.06(syst) \quad (4.2)$$

$$S_{D^{*-}D^+} = -0.29 \pm 0.33(stat) \pm 0.07(syst) \quad C_{D^{*-}D^+} = 0.17 \pm 0.24(stat) \pm 0.04(syst) \quad (4.3)$$

$$S_{D^+D^-} = -0.29 \pm 0.63(stat) \pm 0.06(syst) \quad C_{D^+D^-} = 0.11 \pm 0.35(stat) \pm 0.06(syst) \quad (4.4)$$

5. Summary

We have measured time-dependent CP parameters in various neutral B decays to charm and charmonium final states. No direct CP violation has been observed. The results for the sine term (which is equal to $-\eta_{CP} \sin(2\beta)$ in the SM and in the absence of significant penguin contributions) are all consistent.

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