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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 $\Upsilon(4S) \to B^0\bar{B}^0$ decay, the SM predicts the decay rate $f_+(f_-)$ when the other B meson B_{tag} has been determined to be B^0 ($\bar{B}^0$):

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

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 eigensates $|B_{H/L} >= p|B^0 > \pm q|\bar{B}^0 >$, and A_f and $\bar{A}_f$ are the decay amplitude for $B^0 \to f$ and $\bar{B}^0 \to f$ 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:

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

2. Measurement of *CP* asymmetry in $B^0 \to (c\bar{c})K^{0(*)}$ 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 $227 \times 10^6 \Upsilon(4S) \to B\bar{B}$ 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 paramaters 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]:

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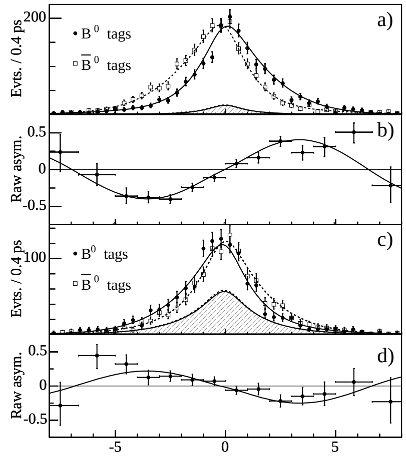

Figure 1: a) Number of $\eta_{CP} = -1$ candidates ($J/\psi\ K^0_S$, $\psi(2S)\ K^0_S$, $\chi_{c1}\ K^0_S$ and $\eta_c\ K^0_S$) in the signal region with a B^0 tag N_{B^0} and with a $\bar{B}^0$ tag $N_{\bar{B}^0}$, and b) the raw asymmetry A^{raw}_{CP}, as a function of Δt. Figures c) and d) are the corresponding plots for the $\eta_{CP} = +1$ mode $J/\psi\ K^0_L$. 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.

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

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

The $B^0 \to J/\psi\,\pi^0$ decay is a Cabibbo and color-suppressed $b \to c\bar{c}d$ 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 $b \to c\bar{c}d$ tree amplitude is the same as for the $b \to c\bar{c}s$ transitions (measured through $B \to (c\bar{c}K^{0(*)}$ modes), but is different from the penguin amplitudes. Therefore if penguin amplitudes contribute significantly to the $B^0 \to J/\psi\,\pi^0$ decay, values of S and C will differ from $-\sin(2\beta)$ and zero [6].

The signal is isolated using the two kinematic variables $m_{\rm ES}$ 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 $m_{\rm ES}$, ΔE, F and Δt distributions. From a data sample of approximately $232 \times 10^6 \Upsilon(4S) \to B\bar{B}$ decays, the fit returns $109 \pm 12(stat)$ signal events and the *CP* parameters [7]:

$$S = -0.68 \pm 0.30(stat) \pm 0.04(syst) \qquad C = -0.21 \pm 0.26(stat) \pm 0.09(syst) \tag{3.1}$$

These values are consistent with the SM expectations for a tree-dominated $b \to c\bar{c}d$ 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 $B^0 \to D^{*+}D^{*-}$ and $B^0 \to D^{(*)\pm}D^{\mp}$ In a data sample of approximately $232 \times 10^6 \Upsilon(4S) \to B\bar{B}$ decays. These color-allowed decays are dominated by the $b \to c\bar{c}d$ 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 $B^0 \to D^{*+}D^{*-}$ 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 likehood fits of B_{rec} and B_{flav} samples on Δt distributions and $m_{\rm ES}$, and $\cos(\theta_{tr})$ for the $B^0 \to D^{*+}D^{*-}$ 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 $B^0 \to D^{*+}D^{*-}$, 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 $B^0 \to D^{*+}D^{*-}$, $B^0 \to D^{*-}D^{+}$, $B^0 \to D^{*+}D^{-}$, and $B^0 \to D^{+}D^{-}$ decay modes, respectively. The results for the *CP* parameters are [9]:

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

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

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

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

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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