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CP Violation in B^0 decays to Charmonium and Charm Final States at *BABAR*

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We report on measurements of time-dependent CP-violation asymmetries in neutral B meson decays to charmonium and charm final states. The results are obtained from a data sample of $(467 \pm 5) \times 10^6$ $\Upsilon(4S) \to B\overline{B}$ decays collected with the *BABAR* detector at the PEP-II B factory.

1. Introduction

In the Standard Model (SM), CP violation is described by the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix, V [1]. In particular an irreducible complex phase in the 3×3 mixing matrix is the source of all the SM CP violation. Measurements of time-dependent CP asymmetries in the B^0 meson decays, through the interference between decays with and without $B^0 - \overline{B}^0$ mixing, have provides stringent test on the mechanism of CP violation in the SM.

In this paper, we present the most updated measurements of CP violation in neutral B meson decays to charmonium and charm final states at *BABAR* . The data used in this analysis were collected with the *BABAR* detector operating at the PEP-II B Factory located at the Stanford Linear Accelerator Center. The *BABAR* dataset comprises $(467{\pm}5){\times}10^6$ $B\overline{B}$ pairs collected from 1999 to 2007 at the center-of-mass (CM) energy $\sqrt{s} = 10.58\,\mathrm{GeV}$, corresponding to the $\Upsilon(4S)$ resonance.

2. Analysis Technique

To measure time-dependent CP asymmetries, we typically fully reconstruct a neutral B meson decaying to a common final state ($B_{\rm rec}$). We identify (tag) the initial flavor of the $B_{\rm rec}$ candidate using information from the other B meson ($B_{\rm tag}$) in the event. The decay rate g_+ (g_-) for a neutral B meson decaying to a CP eigenstate accompanied by a B^0 ($\overline{B}^0$) tag can be expressed as

$$g_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left\{(1 \mp \Delta w) \pm (1-2w) \times \Big[-\eta_f S \sin(\Delta m_d \Delta t) - C\cos(\Delta m_d \Delta t)\Big]\right\} \tag{1}$$

where

$$S = -\eta_f \frac{2\,\mathcal{I}m\,\lambda}{1+|\lambda|^2}, \quad C = \frac{1-|\lambda|^2}{1+|\lambda|^2}, \tag{2}$$

the CP eigenvalue $\eta_f = +1$ (-1) for a CP even (odd) final state, $\Delta t \equiv t_{\rm rec} - t_{\rm tag}$ is the difference between the proper decay times of $B_{\rm rec}$ and $B_{\rm tag}$, τ_{B^0} is the neutral B lifetime, and Δm_d is the mass difference of the B meson mass eigenstates determined from B^0-$\overline{B}^0$ oscillations [2]. We assume that the corresponding decay-width difference $\Delta\Gamma_d$ is zero. Here, $\lambda = (q/p)(\bar{A}/A)$, where q and p are complex constants that relate the B-meson flavor eigenstates to the mass eigenstates, and $\bar{A}/A$ is the ratio of amplitudes of the decay without mixing of a $\overline{B}^0$ or B^0 to the final state under study. The average mistag probability w describes the effect of incorrect tags, and Δw is the difference between the mistag probabilities for B^0 and $\overline{B}^0$ mesons. The sine term in Eq. 1 results from the interference between

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direct decay and decay after $B^0 - \overline{B}^0$ oscillation. A non-zero cosine term arises from the interference between decay amplitudes with different weak and strong phases (direct *CP* violation $|\bar{A}/A| \neq 1$) or from *CP* violation in $B^0 - \overline{B}^0$ mixing ($|q/p| \neq 1$).

In the SM, *CP* violation in mixing is negligible. When only one diagram contributes to the decay process and no other weak phase appears in the process, we expect $C = 0$ and $S = -\eta_f \sin 2\beta$ for B^0 decay that is governed by a $b \to c$ transition, where $\beta \equiv \arg\left[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right]$.

3. $B^0 \to (c\bar{c})K^{(*)0}$

In the SM, the decay $B^0 \to (c\bar{c})K^{(*)0}$ is dominated by a color-suppressed $b \to c\bar{c}s$ tree diagram and the dominate penguin diagram has the same weak phase. As a result, the parameter $C = 0$ and $S = -\eta_f \sin 2\beta$ are valid to a good accuracy. Recent theoretical calculations suggest that the correction on S is of the order of $10^{-3} - 10^{-4}$ [3], well below the precision of the current experimental measurement.

At *BABAR* , we reconstruct B^0 decays to the final states $J/\psi K_S^0$, $J/\psi K_L^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$, $\eta_c K_S^0$, and $J/\psi K^{*0}$ ($K^{(*)0} \to K_S^0\pi^0$). The $J/\psi K_L^0$ final state is *CP* even, and the $J/\psi K^{*0}$ final state is an admixture of *CP* even and *CP* odd amplitudes. Ignoring the angular information in $J/\psi K^{*0}$ results in a dilution of the measured *CP* asymmetry by a factor $1 - 2R_\perp$, where $R_\perp$ is the fraction of the L=1 contribution. In Ref. [4] we have measured $R_\perp = 0.233 \pm$ (stat) $\pm\, 0.005$ (syst), which gives an effective $\eta_f = 0.504 \pm 0.033$ for $f = J/\psi K^{*0}$, after acceptance corrections. By assuming the same *CP* asymmetries for all the final states, we measure [5]

$$\begin{aligned} S_f &= 0.691 \pm 0.029\,(\text{stat}) \pm 0.014\,(\text{syst}), \\ C_f &= 0.026 \pm 0.020\,(\text{stat}) \pm 0.016\,(\text{syst}), \end{aligned}$$

where we define $C_f = \eta_f C$ and $S_f = \eta_f S$ to be consistent with other time-dependent *CP* asymmetry measurements. In addition, *BABAR* also performs measurements, including systematic uncertainties, using individual mode, because the theoretical corrections could in principle be different among those modes. The complete results can be found in reference [5]. Our result is consistent with the SM expectation that $C_f = 0$ and $S_f = \sin 2\beta$, as well as our previous measurement [6]. Figure 1 shows the Δt distributions and asymmetries in yields between B^0 tags and $\overline{B}^0$ tags for the $\eta_f = -1$ and $\eta_f = +1$ samples as a function of Δt, overlaid with the projection of the likelihood fit result.

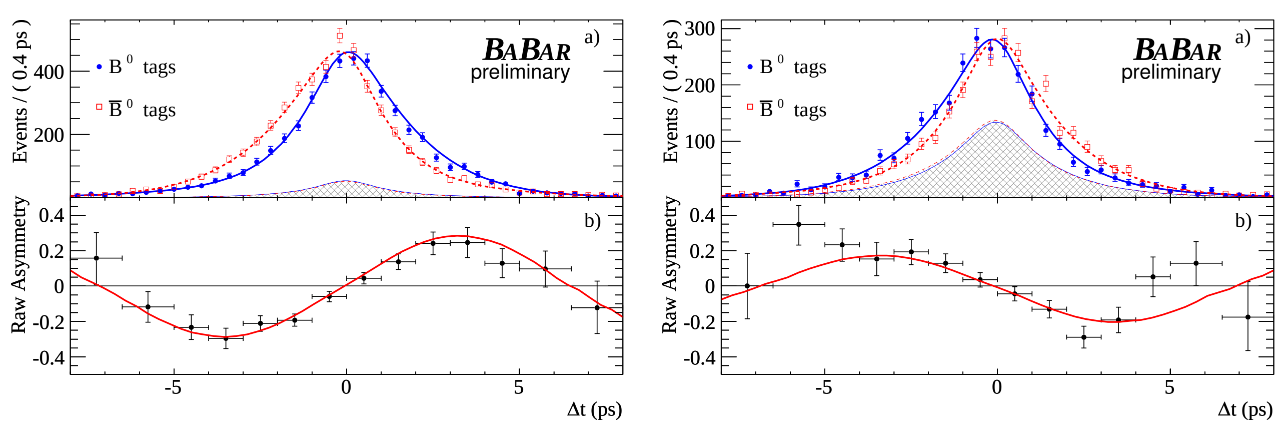

Figure 1: Left: a) Number of $\eta_f = -1$ candidates ($J/\psi K_S^0$, $\psi(2S)K_S^0$, $\chi_{c1}K_S^0$, and $\eta_c K_S^0$) in the signal region with a B^0 tag (N_{B^0}) and with a $\overline{B}^0$ tag ($N_{\overline{B}^0}$), and b) the raw asymmetry, $(N_{B^0} - N_{\overline{B}^0})/(N_{B^0} + N_{\overline{B}^0})$, as functions of Δt; Right: the corresponding distributions for the $\eta_f = +1$ mode $J/\psi K_L^0$. The solid (dashed) curves represent the fit projections in Δt for B^0 ($\overline{B}^0$) tags. The shaded regions represent the estimated background contributions.

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4. $B^0 \to D^{(*)\pm}D^{(*)\mp}$

The $B^0 \to D^{(*)\pm}D^{(*)\mp}$ decays are dominated by a color-allowed tree-level $b \to c\bar{c}d$ transition. When neglecting the penguin (loop) amplitude, the mixing-induced *CP* asymmetry of $B^0 \to D^{(*)\pm}D^{(*)\mp}$ is also determined by $\sin 2\beta$ [7]. The effect of this assumption has been estimated in models based on factorization and heavy quark symmetry, and the corrections are expected to be a few percent [8, 9]. A large deviation of S in $B^0 \to D^{(*)\pm}D^{(*)\mp}$ with respect to $\sin 2\beta$ determined from $b \to (c\bar{c})s$ transition could indicate physics beyond the SM [10–12].

The final state D^+D^- is a *CP* eigenstate so $S = -\sin 2\beta$ and $C = 0$ in the SM when neglecting the penguin contribution. Most recently, the Belle collaboration reported evidence of large direct *CP* violation in $B^0 \to D^+D^-$ where $C_{D^+D^-} = -0.91 \pm 0.23\,(\text{stat}) \pm 0.06\,(\text{syst})$ [13], in contradiction to the SM expectation. This has not been observed by BABAR nor is it verified by the other $B^0 \to D^{*\pm}D^{(*)\mp}$ decay modes [14, 15] which involve the same quark-level diagrams. We updated our measurement with the complete $\Upsilon(4S)$ data sample collected at BABAR and find [16]

$$\begin{aligned} S_{D^+D^-} &= -0.63 \pm 0.36\,(\text{stat}) \pm 0.05\,(\text{syst}), \\ C_{D^+D^-} &= -0.07 \pm 0.23\,(\text{stat}) \pm 0.03\,(\text{syst}), \end{aligned}$$

which is consistent with the SM with small penguin contributions.

The final state $D^{*\pm}D^{*\mp}$ is a mixture of *CP* even and *CP* odd states. The fraction of *CP* odd component R_T is determined to be $R_T = 0.158 \pm 0.028(\text{stat}) \pm 0.006(\text{syst})$ using a transversity analysis at BABAR [16] . We performed a combined analysis of the angular distribution and its time-dependence to extract the time-dependent *CP* asymmetry. We measure [16]

$$\begin{aligned} S_+ &= -0.76 \pm 0.16\,(\text{stat}) \pm 0.04\,(\text{syst}), \\ C_+ &= 0.02 \pm 0.12\,(\text{stat}) \pm 0.02\,(\text{syst}), \\ S_\perp &= -1.81 \pm 0.71\,(\text{stat}) \pm 0.16\,(\text{syst}), \\ C_\perp &= 0.41 \pm 0.50\,(\text{stat}) \pm 0.08\,(\text{syst}), \end{aligned}$$

where S_+ and C_+ are the *CP* asymmetries of the *CP* even component, and $S_\perp$ and $C_\perp$ are the *CP* asymmetries of the *CP* odd component. In the absence of penguin contribution, $S_+ = S_\perp = -\sin 2\beta$ and $C_+ = C_\perp = 0$. Additionally we fit the data constraining $S_+ = S_\perp = S_{D^{*+}D^{*-}}$ and $C_+ = C_\perp = C_{D^{*+}D^*}$ and find [16]

$$\begin{aligned} S_{D^{*+}D^{*-}} &= -0.71 \pm 0.16\,(\text{stat}) \pm 0.03\,(\text{syst}), \\ C_{D^{*+}D^{*-}} &= 0.05 \pm 0.09\,(\text{stat}) \pm 0.02\,(\text{syst}). \end{aligned}$$

Because $B^0 \to D^{*\pm}D^{\mp}$ is not a *CP* eigenstate, the expressions for S and C are related, $S_{D^{*\pm}D^{\mp}} = -\sqrt{1 - C_{D^{*\pm}D^{\mp}}}\sin(2\beta_{\text{eff}} \pm \delta)$, where δ is the strong phase difference between $B^0 \to D^{*+}D^-$ and $B^0 \to D^+D^{*-}$ [17]. When neglecting the penguin contributions, $\beta_{\text{eff}} = \beta$, and $C_{D^{*+}D^-} = -C_{D^+D^{*-}}$. We measure [16]

$$\begin{aligned} S_{D^{*+}D^-} &= -0.62 \pm 0.21\,(\text{stat}) \pm 0.03\,(\text{syst}), \\ S_{D^+D^{*-}} &= -0.73 \pm 0.23\,(\text{stat}) \pm 0.05\,(\text{syst}), \\ C_{D^{*+}D^-} &= 0.08 \pm 0.17\,(\text{stat}) \pm 0.04\,(\text{syst}), \\ C_{D^-D^{*+}} &= 0.00 \pm 0.17\,(\text{stat}) \pm 0.03\,(\text{syst})\,. \end{aligned}$$

All of the S parameters of $B^0 \to D^{(*)\pm}D^{(*)\mp}$ measured in BABAR are consistent with the value of $\sin 2\beta$ measured in $b \to c\bar{c}s$ transitions and with the expectation from the SM for small penguin contributions. The C parameters are consistent with zero in all modes. In particular, we see no evidence of the large direct *CP* violation reported by the Belle Collaboration in the $B^0 \to D^+D^-$ channel.

5. $B^0 \to J/\psi\ \pi^0$

The $B^0 \to J/\psi\pi^0$ decay has the same quark level diagrams as $J/\psi K^0$ except that the s quark in $b \to c\bar{c}s$ is substituted by a d quark. Therefore, the dominant tree diagram is Cabibbo suppressed compared to that of $J/\psi K^0$. However, unlike $J/\psi K^0$, the dominant penguin diagram in $J/\psi\pi^0$, whose CKM element factor is in the same order as the tree, has a different weak phase from the tree. Therefore the deviation in S from the $\sin 2\beta$ of $J/\psi K^0$ could be substantial. This mode is also useful to constrain the penguin pollution in $B^0 \to (c\bar{c})K^0$ mode in a more model-independent way (assuming SU(3) symmetry) [18].

BABAR has recently updated the *CP* violation measurement in this decay. We measure [19]

$$S = -1.23 \pm 0.21\,(\text{stat}) \pm 0.04\,(\text{syst}),$$
$$C = -0.20 \pm 0.19\,(\text{stat}) \pm 0.03\,(\text{syst}).$$

The significance of S or C being nonzero has been estimated to be $4.0\,\sigma$ using ensembles of MC simulated experiments including the systematic uncertainties. This constitutes evidence of the *CP* violation in $B^0 \to J/\psi\pi^0$ decay. The numerical values of S and C are consistent with the SM expectations for a tree-dominated $b \to c\bar{c}d$ transition.

6. Conclusion

We have presented most unadapted measurements of time-dependent *CP*-violation asymmetries in neutral B meson decays to charmonium and charm final states from *BABAR* experiment. The results are in a good agreement with the SM expectations.

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