CP violation in B decays to charm and charmonium at Belle

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We present the study of CP violation in charm and charmonium decays, using a data sample corresponding to \(657 \times 10^6 \) \(B\bar{B}\) events collected with the Belle detector at the \(\Upsilon(4S)\) resonance at the KEKB asymmetric-energy \(e^+e^-\) collider. We report measurements of the polarization fraction and time-dependent CP-violation parameters of the decay \(B^0 \rightarrow D^+D^-\) and of the branching fraction and charge asymmetry in the decay of the Cabibbo- and color-suppressed process \(B^\pm \rightarrow \psi(2S)\pi^\pm\).

1. INTRODUCTION

The study of exclusive \(B\) meson decays to charm and charmonium has played an important role in exploring CP violation [1–3]. Amongst them the Cabibbo-suppressed decays have an increased sensitivity to New Physics effects and can be studied at the \(B\) factories which, due to their high integrated luminosities, overcome the suppression factor. The \(B^0 \rightarrow D^+D^-\) and \(B^- \rightarrow \psi(2S)\pi^-\) decay proceed primarily via a \(b \rightarrow c\bar{c}d\) tree diagram while penguin contributions are expected to be small in the Standard Model (SM). A large deviation of the measured CP parameters from the SM prediction can be a hint of New Physics.

2. DATASET AND EVENT RECONSTRUCTION

Both analyses are based on a data sample containing 657 million \(B\bar{B}\) pairs, collected with the Belle detector [4] at the KEKB asymmetric-energy \(e^+e^-\) collider [5] operating at the \(\Upsilon(4S)\) resonance. The \(\Upsilon(4S)\) meson is produced with a Lorentz boost \(\beta\gamma = 0.425\) along the \(z\) axis, opposite to the positron beam direction, and decays mainly into a \(B^0\bar{B}^0\) or a \(B^+B^-\) pair.

The reconstructed \(B\) candidates are discriminated from background using the energy difference \(\Delta E \equiv E_{CM}^B - E_{CM}^{CM}\) and the beam-constrained mass \(M_{bc} \equiv \sqrt{(E_{CM}^{CM})^2 - (p_{CM}^B)^2}\), where \(E_{CM}^{CM}\) is the beam energy in the center-of-mass (CM) system and \(E_{CM}^B\) and \(p_{CM}^B\) are the CM energy and momentum of the \(B\) candidate.

3. \(B^- \rightarrow \psi(2S)\pi^-\)

3.1. Theoretical Motivation

The main \(B^- \rightarrow \psi(2S)\pi^-\) diagram is not only Cabibbo-suppressed but also color-suppressed. A measurement of its branching fraction, unknown so far, is shown in this paper. Assuming tree dominance and factorization, the branching fraction \(\mathcal{B}(B^- \rightarrow \psi(2S)\pi^-)\) is expected to be about 5% of that of the Cabibbo-favored mode \(B^- \rightarrow \psi(2S)K^-\) [6].

Furthermore under these assumptions, CP violation should be negligibly small. However if penguin contributions or new physics effects are present, a non-zero charge asymmetry can occur.

3.2. Results

The \(\psi(2S)\) meson is reconstructed through the \(\ell^+\ell^-\) and \(J/\psi\pi^+\pi^-\) decay channels, where the \(J/\psi\) decays to \(\ell^+\ell^-\) (\(\ell = e\) or \(\mu\)). Inclusion of charge-conjugate modes is implied throughout the paper. Contamination from the \(B^- \rightarrow \psi(2S)K^-\) decays, where a kaon is misinterpreted as a pion, results in a peak at \(\Delta E \approx -0.07\) GeV, which is
which is consistent with no direct CP violation. Finally we measure

$$B(B^- \rightarrow \psi(2S)\pi^-) = (3.99 \pm 0.36 \text{ (stat)} \pm 0.17 \text{ (syst)})\%,$$

which is consistent with the theoretical prediction of the factorization hypothesis.

4. $B^0 \rightarrow D^{*+}D^{*-}$

4.1. Theoretical Motivation

The time-dependent decay rate of a neutral $B$ meson to a CP eigenstate, such as $D^{*+}D^{*-}$, is given by:

$$P(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left\{ 1 + q \left[ S \sin(\Delta m_d \Delta t) + A \cos(\Delta m_d \Delta t) \right] \right\},$$

where $q = +1(-1)$ when the other $B$ meson in the event decays as a $B^0$ ($\bar{B}^0$) and $\Delta t = t_{CP} - t_{tag}$ is the proper time difference between the two $B$ decays in the event, $\tau_{B^0}$ is the neutral $B$ lifetime, $\Delta m_d$ the mass difference between the two $B^0$ mass eigenstates. The CP-violating parameters are defined as

$$S = \frac{23(\lambda)}{|\lambda|^2 + 1}, \quad A = \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1},$$

where $\lambda$ is a complex observable depending on the $B^0$ and $\bar{B}^0$ decay amplitudes to the final state and the relation between the $B$ meson mass eigenstates and its flavor eigenstates. When ignoring penguin corrections, the SM predictions for the $CP$ parameters are $A_{D^{*-}D^{*-}} = 0$ and $S_{D^{*-}D^{*-}} = -\eta_{D^{*-}D^{*-}} \sin 2\phi_1$, where $\phi_1 = \arg[-V_{td}V_{tb}^*]/|V_{td}V_{tb}|$ and $\eta_{D^{*-}D^{*-}}$ is the $CP$ eigenvalue of $D^{*+}D^{*-}$, which is +1 when the decay proceeds through the $S$ or $D$ wave, or −1 for the $P$ wave. A significant shift of the $CP$ parameters from the SM predictions can be a sign for New Physics.
4.2. Yield and angular analysis

The $D^{*\pm}$ mesons are reconstructed in the $D^0\pi^+$ and $D^+\pi^0$ modes. The signal is extracted from a two-dimensional unbinned maximum likelihood fit in the $M_{bc}$ vs. $\Delta E$ plane. We obtain $553 \pm 30$ signal events with a signal purity of $55\%$. The first two plots in Fig. 2 show the projections of the fitted $M_{bc}$ and $\Delta E$ distributions in the signal region.

To obtain the $CP$-odd fraction we perform a time-integrated angular analysis in the transversity basis [7]. The differential decay rate as a function of the transversity angle $\theta_{tr}$ reads

$$\frac{1}{\Gamma} \frac{d\Gamma_{B \rightarrow D^*+D^-}}{d \cos \theta_{tr}} = \frac{3}{4} R_0 \sin^2 \theta_{tr} + \frac{3}{2} R_\perp \cos^2 \theta_{tr} + \frac{3}{4} R_\parallel \sin^2 \theta_{tr}$$

where $R_{0,\parallel}$ and $R_\perp$ are the $CP$-even and $CP$-odd fractions of the three transversity components respectively. A one-dimensional fit of the $\cos \theta_{tr}$ distribution allows the extraction of the $CP$-odd fraction. Its distortion due to the angular resolution and the slow pion reconstruction efficiency is modeled using signal MC samples. The fraction $R_\parallel/(R_0 + R_\parallel)$ is taken from the previous Belle analysis [3]. The signal-to-background ratio is determined on an event-by-event basis using the $M_{bc} - \Delta E$ distribution. The result (shown in the right plot of Fig. 2) is

$$R_\perp = 0.125 \pm 0.043\text{(stat)} \pm 0.023\text{(syst)}.$$ (7)

4.3. Time-dependent $CP$ violation measurement

Because the $B^0$ and $\bar{B}^0$ are approximately at rest in the $Y(4S)$ CM frame, the $\Delta t$ value can be determined from the separation in $z$ of the two decay vertices, $\Delta \gamma \simeq \Delta z/\beta c$, where $c$ is the speed of light. To obtain the $\Delta t$ distribution, we reconstruct the tag-side $B$ vertex and its flavor inclusively from properties of particles that are not associated with the reconstructed $B^0 \rightarrow D^{*+}D^{*-}$ decay [8]. The tagging information is represented by two parameters, the flavor of the tagging $B^0$, $q$, and the tagging quality given by seven $r$ intervals from $r = 0$ meaning no flavor discrimination to $r = 1$ for unambiguous flavor assignment. Equation 4 is modified to incorporate the effect of incorrect flavor assignment, the $CP$-odd dilution, and the description of background events. The signal-to-background fraction is obtained on an event-by-event basis, using the previous fits of the $M_{bc}$, $\Delta E$ and $\cos \theta_{tr}$ distributions. The free parameters in the fit are $A_{D^+D^-}$ and $S'_{D^+D^-} = S_{D^+D^-}/\eta_{D^+D^-}$; these are determined by maximizing an unbinned likelihood function for all events in the fit region. The result is

$$A_{D^+D^-} = 0.15 \pm 0.13\text{(stat)} \pm 0.04\text{(syst)},$$

$$S'_{D^+D^-} = -0.96 \pm 0.25\text{(stat)} \pm 0.12\text{(syst)},$$ (8)
Figure 3: Top: $\Delta t$ distribution of well-tagged $B^0 \rightarrow D^{+}\bar{D}^{-}$ candidates ($r > 0.5$) for $q = +1$ and $q = -1$. The gray area is the background contribution while the solid and dashed curves are the superposition of the total PDFs for well-tagged $q = -1$ (solid line) and $q = +1$ (dotted line) events respectively. Bottom: fitted raw asymmetry of the two top distributions.

with a statistical correlation of 10.7%. The total significance of non-zero values of $S'$ and $A$ is 3.1 $\sigma$. We define the raw asymmetry in each $\Delta t$ bin as $(N_+ - N_-)/(N_+ + N_-)$, where $N_+ (N_-)$ is the number of observed candidates with $q = +1 (-1)$. Figure 3 shows the $\Delta t$ distribution and the raw asymmetry for events with a good-quality tag ($r > 0.5$).

Our measurement of $S'$ and $A$ is consistent with the SM expectation for a tree-dominated $b \rightarrow c \bar{c}d$ transition.

5. Conclusion

We reported a measurement of the $CP$-violating parameters in $B^- \rightarrow \psi(2S)\pi^-$ and $B^0 \rightarrow D^{*+}D^{-}$ decay using 657 million $B\bar{B}$ pairs recorded with the Belle detector. Both measurements are compatible with the SM predictions in absence of penguins. The branching fraction of $B^- \rightarrow \psi(2S)\pi^-$ is extracted as well as its ratio with respect to $B^- \rightarrow \psi(2S)K^-$. The result supports the factorization hypothesis. In the $B^0 \rightarrow D^{*+}D^{-}$ analysis the $CP$-odd fraction is obtained to allow for an undiluted measurement of $\sin 2\phi_1$.

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