Observation of $B_s^0 \rightarrow D_s^{(*)-} \pi^+$, $B_s^0 \rightarrow D_s^{(*)-} \rho^+$ and $B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-}$ and Estimate of $\Delta \Gamma_{CP}$ at Belle

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The large data sample being recorded with the Belle detector at the $\Upsilon(5S)$ energy provides a unique opportunity to study the less-well-known $B_s$ meson decays. Following our recent measurement of $B_s^0 \rightarrow D_s^- \pi^+$ in a sample of $23.6 \text{ fb}^{-1}$, we extend the analysis to include decays with photons in the final state. Using the same sample, we report the first observation of three other dominant exclusive $B_s^0$ decays, in the modes $B_s^0 \rightarrow D_s^{(*)-} \pi^+$, $B_s^0 \rightarrow D_s^- \rho^+$ and $B_s^0 \rightarrow D_s^{(*)-} \rho^+$. We measure their respective branching fractions and, using helicity-angle distributions, the longitudinal polarization fraction of the $B_s^0 \rightarrow D_s^{(*)-} \rho^+$ decay.

We also present a measurement of the branching fractions for the decays $B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-}$. In the heavy quark limit, this branching fraction is directly related to the width difference between the $B_s$ CP-even and CP-odd eigenstates.
1. Introduction

Beginning in 2005, the Belle experiment running KEKB $e^+e^-$ collider [1] has recorded several data sets at the center-of-mass energy corresponding to the $\Upsilon(5S)$ resonance. Belle has used this data sets to measure several $B^0_d$ properties and branching fractions. The total of 120 fb$^{-1}$ at the $\Upsilon(5S)$ ($\sqrt{s} \approx 10.87$ GeV) has been recorded. The results presented here correspond to the first 23.6 fb$^{-1}$.

The total $e^+e^-$ to $b\bar{b}$ cross section at the $\Upsilon(5S)$ energy was measured to be $\sigma_{bb} = (302 \pm 14)$ pb [2, 3], with the fraction $f_{e} = \sigma(e^+e^- \rightarrow B_s^{(*)}\bar{B}_s^{(*)})/\sigma_{bb} = (19.3 \pm 2.9\%)$ [4]. The dominant $B_s^0$ production mode is $e^+e^- \rightarrow B_s^0\bar{B}_s^0$, with a fraction $f_{B_s^0} = (90.1^{+3.8}_{-4.0} \pm 0.2\%)$ of the $b\bar{b} \rightarrow B_s^{(*)}\bar{B}_s^{(*)}$ events [5]. Thus for 23.6 fb$^{-1}$ the total number of $e^+e^- \rightarrow B_s^0\bar{B}_s^0$ events is $(1.24 \pm 0.2) \times 10^6$.

All signal $B_s^0$ decays are fully reconstructed from final-state particles using two quantities: the beam-energy-constrained mass $M_{bc} = \sqrt{E^2_b - P^2_{B_s}}$, and the energy difference $\Delta E = E_B - E_{\bar{B}_s}$, where $P_{B_s}$ and $E_B$ are the reconstructed momentum and energy of the $B_s^0$ candidate, and $E_{\bar{B}_s}$ is the beam energy. These quantities are evaluated in the $e^+e^-$ center-of-mass frame. Although the $B_s^0$ always decays to $B_s^0\gamma$, the $\gamma$ is not reconstructed because of its extremely low momentum.

2. Observation of $B_s^0 \rightarrow D_s^-\pi^+$ and $D_s^{(*)}-\rho^+$ Decays and Polarization Measurement of $B_s^0 \rightarrow D_s^-\rho^+$

Three CKM-favored decays with relatively large branching fractions, $B_s^0 \rightarrow D_s^-\pi^+$ and $D_s^{(*)}-\rho^+$, have been observed recently by Belle [6]. Three $D_s^-$ decay modes are considered: $\phi(\rightarrow K^+K^-)\pi^+$, $K_S(\rightarrow \pi^+\pi^-)K^+$ and $K^{*0}(\rightarrow K^+\pi^-)K^+$. Since only four charged tracks and up to one $\gamma$ and $\pi^0$ are required, these final states have relatively large signals. The continuum events are removed using the ratio of the second to zeroth Fox-Wolfram moments [7]. This ratio differs for spherical $B$ events and jet-like continuum events.

Only one $B_s^0$ candidate is allowed per event. This candidate is chosen based on the intermediate-particle reconstructed masses. The $M_{bc}$ and $\Delta E$ distributions of the selected $B_s^0$ candidates are shown in Figure 1. For the $B_s^0 \rightarrow D_s^-\rho^+$ candidates, the helicity angles $\theta_{D_s^-}$ and $\theta_{\rho^+}$ are also reconstructed. These are defined as the angle between the $D_s^-$ or $\pi^+$ and the opposite direction of the $B_s^0$ in the $D_s^-\rho^+$ rest frame. The distributions of $\cos \theta_{D_s^-}$ and $\cos \theta_{\rho^+}$ are fitted to determine the longitudinal polarization fraction $f_\perp$ (see Table 1).

3. Observation of $B_s \rightarrow D_s^{(*)}-D_s^{(*)}$ Decays and a Determination of the $\Delta \Gamma_s$

Decays of $B_s \rightarrow D_s^{(*)}-D_s^{(*)}$ are interesting due to their large CP-even fraction. The pure CP-even $D_s^+$ state and predominantly CP-even $D_s^0D_s^{(*)}$ states are Cabibbo-favored and expected to dominate the width difference of the $B_s^0 - \bar{B}_s^0$ system. In the heavy quark limit, assuming negligible CP violation, the relative width difference is $\Delta \Gamma_s^{CP}/\Gamma_s = 2\beta/(1 - \beta)$, where $\beta$ is the total branching fraction of $B_s \rightarrow D_s^{(*)}-D_s^{(*)}$ decays [8].

For this study [9], $D_s^+$ candidates are reconstructed in six modes, $\phi\pi^+, K_SK^+, K^{*0}K^+, \phi\rho^+, K^+K_S$ and $K^+K^{*0}$. $B_s^0$ candidates are reconstructed from two oppositely charged $D_s^{(*)}$ mesons. As the daughter photon of the $D_s^*$ has very low momentum, more than half of the events yield more than one $B_s^0$ candidate sharing the same $D_s$ pair. Only one candidate per event is selected.
using a selection criteria based on $M_{D_s}$ and $M_{D_s} - M_{D_s}$ information. After rejecting continuum events using a Fisher discriminant based on a set of modified Fox-Wolfram moments [7, 10], the remaining background events are largely $B_{(s)} \rightarrow D_{s}^{(*)} X$ decays, where $X$ is an accidental particle combination with a reconstructed mass within the $D_s$ mass window. The $B^0 \rightarrow D_s^+ D_s^{-}, D_s^{-} D_s^{+},$ and $D_s^{+} D_s^{-} + 1$ modes are fitted simultaneously; the fit projections are shown in Figure 2.

The signal yields, branching fractions, and resulting value of $\Delta \Gamma/\Gamma_{CP}$ are listed in Table 1. Various systematic uncertainties are studied, and the resulting systematic errors are listed after the statistical errors. The second systematic error is due to uncertainty of $f_s$ for $B_s^0 \rightarrow D_s^{(*)} \pi^+$, $D_s^{(*)} \rho^+$ modes. For $B^0 \rightarrow D_s^{(*)} D_s^{(*)}$ modes, it also includes uncertainties of $D_s$ branching fractions, $\sigma_T(55)$, and $f_{BS/BS}$. Our results are in good agreement with the theoretical predictions [11, 12] and existing measurements[13].

Figure 1: Projections of $B^0_s \bar{B}_s^0$ signal region in $M_{bc}$ and $\Delta E$ for fits of $B^0_s \rightarrow D_s^{+} \pi^+$ (top-left), $D_s^+ \rho^+$ (bottom-left), and $D_s^+ \rho^+$ (top-right). The bottom-right figure shows the helicity distributions for $D_s^+ \rho^+$ mode. The solid-blue line represents the total fit, while the red-dashed(black-dotted) curve is the signal(background).

Figure 2: $\Delta E$ (top) and $M_{bc}$ (bottom) distributions for $D_s^+, D_s^{*-}, D_s^{*-} D_s^{+}$ and $D_s^+ D_s^{*}$, from left to right respectively. The red-dashed curve represents correctly reconstructed signal events, the black curve is the total fit.
Observation of $B^0 \rightarrow D_s^- \pi^+$, $B^0_s \rightarrow D_s^{(*)-} \rho^+$ and $B^0 \rightarrow D_s^{(*)+} D_s^{(*)-}$ and Estimate of $\Delta \Gamma_{CP}$

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| Mode | $N_{B_s \bar{B}_s}$ | S | $\varepsilon$ | $\mathcal{B}$(%) | World Average |
|------|-----------------|---|-------------|-------------|--------------|
| $B^0 \rightarrow D_s^- \pi^+$ | $53.4^{+10.3}_{-9.4}$ | 7.1 | $9.13 \times 10^{-2}$ | $0.24^{+0.05}_{-0.04} \pm 0.03 \pm 0.04$ | 1st Measurement |
| $B^0 \rightarrow D_s^- \rho^+$ | $92.2^{+14.2}_{-13.2}$ | 8.2 | $4.40 \times 10^{-2}$ | $0.85^{+0.13}_{-0.12} \pm 0.11 \pm 0.13$ | 1st Measurement |
| $B^0_s \rightarrow D_s^{(*)+} \rho^+$ | $77.8^{+14.5}_{-13.4}$ | 7.4 | $2.67 \times 10^{-2}$ | $1.19^{+0.22}_{-0.20} \pm 0.17 \pm 0.18$ | 1st Measurement |
| $f_t(B^0 \rightarrow D_s^- \bar{D}_s^+)$ | $1.05^{+0.08}_{-0.10} + 0.03$ | | | | 1st Measurement |
| $B^0 \rightarrow D_s^- D_s^+$ | $8.5^{+3.2}_{-2.6}$ | 6.2 | $3.31 \times 10^{-4}$ | $1.03^{+0.39}_{-0.32} + 0.13 \pm 0.21$ | (1.04 ± 0.35)% |
| $B^0_s \rightarrow D_s^{(*)-} D_s^+$ | $9.2^{+2.8}_{-2.4}$ | 6.6 | $1.35 \times 10^{-4}$ | $2.75^{+0.83}_{-0.71} \pm 0.40 \pm 0.56$ | 1st Observation |
| $B^0 \rightarrow D_s^- D_s^+$ | $4.9^{+1.9}_{-1.7}$ | 3.1 | $0.643 \times 10^{-4}$ | $3.08^{+1.22}_{-1.04} + 0.57 \pm 0.63$ | 1st Evidence |
| $B^0_s \rightarrow D_s^{(*)-} D_s^{(*)+}$ | $22.6^{+4.7}_{-3.9}$ | | | | (4.0 ± 1.5)% |
| $\Delta \Gamma_s/\Delta \Gamma$ | $0.147^{+0.036}_{-0.030} + 0.042$ | | | | 0.080 ± 0.030 |

Table 1: Summary of the results. Signal yields in the $B^0_s \bar{B}_s$ production mode, $N_{B_s \bar{B}_s}$; significances, S (including systematics); total signal efficiencies, $\varepsilon$ (including all sub-decay branching fractions); and branching fractions, $\mathcal{B}$. The first error is statistical, while the latter two are systematic and arise from internal and external sources. The significance $S = \sqrt{-2 \ln(L_0/L_{max})}$, where $L_0/L_{max}$ are likelihood values when the signal yield is fixed to zero (floated).

4. Conclusion

We presented recent branching fraction measurements of $B^0_s$ decays obtained from 23.6 fb$^{-1}$ of $\Upsilon(5S)$ data recorded by the Belle experiment. Also, the longitudinal polarization fraction is measured for the $B^0_s \rightarrow D_s^- \rho^+$ mode and $\Delta \Gamma_{s CP}/\Gamma_s$ is estimated using $D_s^{(*)-} D_s^{(*)+}$ modes.

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