δ(5S) AND Bs DECAYS AT BELLE

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Recent results obtained using the data sample of 23.6 fb$^{-1}$ collected on the δ(5S) resonance with the Belle detector at the KEKB asymmetric energy $e^+e^-$ collider are discussed. Measurements of several $B_s^0$ decay branching fractions are reported. Studies of the δ(5S) decays to the channels with $B^+$ and $B^0$ mesons or bottomonium states are discussed.

1 Introduction

During the last several years an opportunity for $B_s^0$ meson studies at the $e^+e^-$ colliders running at the δ(5S) resonance has been extensively explored. The first evidence for $B_s^0$ production at the δ(5S) was found by the CLEO collaboration$^{1,2}$ using a dataset of 0.42 fb$^{-1}$ collected in 2003. To test the feasibility of a $B_s^0$ physics program the Belle collaboration collected at the δ(5S) a dataset of 1.86 fb$^{-1}$ in 2005. After the successful analysis of these data$^{3,4}$, Belle collected a bigger sample of 21.7 fb$^{-1}$ in 2006. More δ(5S) data were taken by Belle in 2008.

The δ(5S) resonance can potentially decay to various final states with $B^+$, $B^0$ and, moreover, $B_s^0$ mesons, because the δ(5S) has a mass exceeding the $B^*$ production threshold. At this energy a $b\bar{b}$ quark pair can be produced and hadronized in various final states, which can be classified as two-body $B_s^0$ channels $B_s^0\bar{B}_s^0$, $B_s^0\bar{B}_s^-$, $B_s^+\bar{B}_s^-$, two-body $B^+/0$ channels $BB$, $B\bar{B}^*$, $B^*\bar{B}$, $B^*\bar{B}^*$, three-body channels $BB\pi$, $BB^*\pi$, $BB^*\pi$, and four-body channel $B\bar{B}\pi\pi$. Here $B$ denotes a $B^+$ or a $B^0$ meson and $\bar{B}$ denotes a $B^-$ or a $\bar{B}^0$ meson, and the excited states decay to their ground states via $B^*\rightarrow B\gamma$ and $B_s^*\rightarrow B_s\gamma$. Moreover a $b\bar{b}$ quark pair can hadronize to a bottomonium state accompanied by $\pi$, $K$, or $\eta$ mesons, for example through the $\delta(5S)\rightarrow \delta(1S)\pi^+\pi^-$ decay. Fractions and decay parameters for all of these channels provide important information about the $b$-quark dynamics.

The $B_s^0$ production rate at the δ(5S) was measured to be $(19.5^{+3.0}_{-2.3})\%$ 5, therefore the δ(5S) could play a similar role for comprehensive $B_s^0$ studies that the δ(4S) has played for $B^+$ and $B^0$ studies. Similar to the experimental technique used at the δ(4S), two variables can be used to identify $B_s^0$ signals at the δ(5S): the energy difference $\Delta E = E_{B_s^0}^{CM} - E_{\text{beam}}^{CM}$ and the beam-energy-constrained mass $M_{bc} = \sqrt{(E_{\text{beam}}^{CM})^2 - (p_{B_s^0}^{CM})^2}$, where $E_{B_s^0}^{CM}$ and $p_{B_s^0}^{CM}$ are the energy and momentum of the $B_s^0$ candidate in the $e^+e^-$ center-of-mass (CM) system, and $E_{\text{beam}}^{CM}$ is the CM beam energy. The $B_s^*\bar{B}_s^*$, $B_s^*\bar{B}_s^-$, $B_s^0\bar{B}_s^*$ and $B_s^0\bar{B}_s^0$ intermediate channels can be distinguished kinematically in the $M_{bc}$ and $\Delta E$ plane, where three well-separated $B_s^0$ signal regions can be defined corresponding to the cases where both, only one, or neither of the $B_s^0$ mesons originate from a $B_s^0$ decay.
2 \( B_s^0 \) decay branching fraction measurements

2.1 Measurement of \( B_s^0 \to D_s^- \pi^+ \) decay and evidence for \( B_s^0 \to D_s^+ K^\pm \) decay

We report here the results from studies of \( B_s^0 \to D_s^- \pi^+ \) and \( B_s^0 \to D_s^+ K^\pm \) decays\(^6\) obtained by the Belle collaboration with 23.6 fb\(^{-1}\) at the \( \Upsilon(5S) \). In this analysis \( D_s^- \) candidates are reconstructed in the \( \phi\pi^- \), \( K^{*0}K^- \) and \( K_S^0K^- \) modes. The \( M_{bc} \) and \( \Delta E \) scatter plots for the \( B_s^0 \to D_s^- \pi^+ \) and \( B_s^0 \to D_s^+ K^\pm \) decays are studied. A clear signal is observed in the \( B_s^0 \to D_s^- \pi^+ \) decay mode, and evidence for the \( B_s^0 \to D_s^+ K^\pm \) decay is also seen. For each mode, a two-dimensional unRestricted extended maximum likelihood fit in \( M_{bc} \) and \( \Delta E \) is performed on the selected candidates. Fig. 1 shows the \( M_{bc} \) and \( \Delta E \) projections in the \( B_s^+B_s^- \) region of the data, together with the fitted functions. The different fitted components are shown with dashed curves for the background, dotted curves for the \( B_s^0 \to D_s^- \pi^+ \) background, and dash-dotted curves for the continuum.

Finally, the branching fractions \( \mathcal{B}(B_s^0 \to D_s^- \pi^+) = (3.67^{+0.35}_{-0.33} \pm 0.65) \times 10^{-3} \) and \( \mathcal{B}(B_s^0 \to D_s^+ K^\pm) = (2.4^{+1.2}_{-1.0} \pm 0.4) \times 10^{-4} \) are measured. The ratio \( \mathcal{B}(B_s^0 \to D_s^+ K^\pm)/\mathcal{B}(B_s^0 \to D_s^- \pi^+) = (6.5^{+3.5}_{-2.9})\% \) is derived; the errors are completely dominated by the low \( B_s^0 \to D_s^+ K^\pm \) statistics.

Comparing the number of events reconstructed in the \( B_s^0 \to D_s^- \pi^+ \) mode in three signal regions, the fraction of \( B_s^0 \to \gamma \) events over all \( B_s^0 \) events was measured to be \( f_{B_s^0 \gamma} = (90.1^{+3.8}_{-4.0} \pm 0.2)\% \). From the \( B_s^0 \) signal fit the mass \( m(B_s^0) = (5416.4 \pm 0.4 \pm 0.5) \) MeV/c\(^2 \) is obtained. The mass difference \( m(B_s^+) - m(B_s^0) \) obtained is 4.0\( \sigma \) larger than the world average for \( m(B^{*0}) - m(B^0) \).

2.2 Observation of \( B_s^0 \to \phi \gamma \) and search for \( B_s^0 \to \gamma \gamma \) decays

The \( B_s^0 \to \phi \gamma \) and \( B_s^0 \to \gamma \gamma \) decays\(^7\) are studied by Belle with 23.6 fb\(^{-1}\) at the \( \Upsilon(5S) \). Within the Standard Model the \( B_s^0 \to \phi \gamma \) decay can be described by a radiative penguin diagram and the corresponding branching fraction is predicted to be \( \sim 4 \times 10^{-5} \). The \( B_s^0 \to \gamma \gamma \) decay is expected to proceed via a penguin annihilation diagram and to have a branching fraction in the range \( (0.5 - 1.0) \times 10^{-6} \). However, the \( B_s^0 \to \gamma \gamma \) decay branching fraction is sensitive to some Beyond the Standard Model contributions and can be enhanced by about an order of magnitude; such enhanced values are not far from the sensitivity expected in this analysis.

The three-dimensional (two-dimensional) unRestricted extended maximum likelihood fit to \( M_{bc} \), \( \Delta E \) and \( \cos \theta_{\phi} \) (\( M_{bc} \) and \( \Delta E \)) is performed for \( B_s^0 \to \phi \gamma \) \( (B_s^0 \to \gamma \gamma) \) decay to extract the signal yield. Fig. 2 shows the \( M_{bc} \) and \( \Delta E \) projections of the data. The points with error bars represent data, the thick solid curves are the fit functions, the thin solid curves are the signal functions, and the dashed curves show the continuum contribution. On the \( M_{bc} \) figure, signals from \( B_s^0 \to \gamma \gamma \) and \( B_s^0 \to \phi \gamma \) appear from left to right. On the \( \Delta E \) figure, due to the requirement \( M_{bc} > 5.4 \) GeV/c\(^2 \) only the \( B_s^0 \to \phi \gamma \) signal contributes.

A clear signal is seen in the \( B_s^0 \to \phi \gamma \) mode. This radiative decay is observed for the first
time and the branching fraction $\mathcal{B}(B_s^0 \rightarrow \phi \gamma) = (5.7_{-1.0}^{+1.8}\text{(stat.)}^{+1.2}_{-1.1}\text{(syst.)}) \times 10^{-5}$ is measured. The obtained value is in agreement with the SM predictions. No significant signal is observed in the $B_s^0 \rightarrow \gamma\gamma$ mode, and an upper limit at the 90% C.L. of $\mathcal{B}(B_s^0 \rightarrow \phi \gamma) < 8.7 \times 10^{-6}$ is set.

2.3 Observation of $B_s^0 \rightarrow J/\psi \phi$ and $B_s^0 \rightarrow J/\psi \eta$ decays

Preliminary results on the $B_s^0 \rightarrow J/\psi \phi$ and $B_s^0 \rightarrow J/\psi \eta$ decay branching fraction measurements are obtained by Belle. The electron mode $J/\psi \rightarrow e^+e^-$ and the muon mode $J/\psi \rightarrow \mu^+\mu^-$ are used to reconstruct $J/\psi$ mesons. The $B_s^0 \rightarrow J/\psi \phi$ decay branching fraction is measured to be $(1.12 \pm 0.25 \pm 0.21) \times 10^{-3}$ and $(1.18 \pm 0.25 \pm 0.22) \times 10^{-3}$ using the electron and muon modes, respectively.

The $B_s^0 \rightarrow J/\psi \eta$ decay branching fraction is measured using the $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow \pi^+\pi^-\pi^0$ modes to reconstruct $\eta$ mesons. The combined value $\mathcal{B}(B_s^0 \rightarrow J/\psi \eta) = (3.69 \pm 0.95 \pm 0.65) \times 10^{-4}$ is obtained, which is about 3 times smaller than that for the $B_s^0 \rightarrow J/\psi \phi$ decay. This ratio agrees with a rough estimate obtained within the quark model, where the $s\bar{s}$ part of the $\eta$ meson wave function is one third, in contrast to the fully $s\bar{s}$ content of $\phi$ mesons.

2.4 First measurement of $B_s^0 \rightarrow X^+\ell^-\nu$ decay

The correlated production of a $D_s^+$ meson and a same-sign lepton at the $\Upsilon(5S)$ resonance is used in this analysis to measure $\mathcal{B}(B_s^0 \rightarrow X^+\ell^-\nu)$. $D_s^+$ candidates are reconstructed in a clean $\phi\pi^+$ mode. Neither the $c\bar{c}$ continuum nor $B^{(*)}\bar{B}^{(*)}$ states (except for a small contribution due to $\sim 19\%$ $B^0$ mixing effect) can result in a same-sign $c$-quark (i.e., $D_s^+$ meson) and primary lepton final state.

Finally, we obtained the semileptonic branching fractions:

$$\mathcal{B}(B_s^0 \rightarrow X^+e^-\nu) = (10.9 \pm 1.0 \pm 0.9)\%$$
$$\mathcal{B}(B_s^0 \rightarrow X^+\mu^-\nu) = (9.2 \pm 1.0 \pm 0.8)\%$$
$$\mathcal{B}(B_s^0 \rightarrow X^+\ell^-\nu) = (10.2 \pm 0.8 \pm 0.9)\%,$$

where the latter one represents an average over electrons and muons. The results are preliminary. The obtained branching fractions can be compared with the PDG value $\mathcal{B}(B^0 \rightarrow X^+\ell^-\nu) = (10.33 \pm 0.28)\%$ for the $B^0 \rightarrow X^+\ell^-\nu$ mode, which is theoretically expected to be approximately the same, neglecting a small possible lifetime difference and small corrections due to electromagnetic and light quark mass difference effects.

3 Study of $\Upsilon(5S)$ decays

3.1 Observation of $\Upsilon(5S) \rightarrow \Upsilon(1S)\pi^+\pi^-\pi^+\pi^-$ and $\Upsilon(5S) \rightarrow \Upsilon(2S)\pi^+\pi^-\pi^+\pi^-$ decays

The production of $\Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$, $\Upsilon(3S)\pi^+\pi^-$, and $\Upsilon(1S)K^+K^-$ final states in a 21.7 fb$^{-1}$ data sample obtained at $e^+e^-$ collisions with CM energy near the peak of the $\Upsilon(5S)$
Table 1: The branching fractions ($\mathcal{B}$) and the partial widths ($\Gamma$) for $\Upsilon(nS) \rightarrow \Upsilon(mS) h^+ h^-$ processes.

| $\Upsilon(5S)$ → | $\mathcal{B}$ (%) | $\Gamma$ (MeV) | $\Upsilon(2S)$ → $\Upsilon(1S) \pi^+ \pi^-$ | $\Gamma$ (MeV) |
|------------------|------------------|--------------|---------------------------------|--------------|
| $\Upsilon(1S) \pi^+ \pi^-$ | $0.53 \pm 0.03 \pm 0.05$ | $0.59 \pm 0.04 \pm 0.09$ | $\Upsilon(2S)$ → $\Upsilon(1S) \pi^+ \pi^-$ | $0.006$ |
| $\Upsilon(2S) \pi^+ \pi^-$ | $0.78 \pm 0.06 \pm 0.11$ | $0.85 \pm 0.07 \pm 0.16$ | $\Upsilon(3S)$ → $\Upsilon(1S) \pi^+ \pi^-$ | $0.0009$ |
| $\Upsilon(3S) \pi^+ \pi^-$ | $0.48^{+0.18}_{-0.15} \pm 0.07$ | $0.52^{+0.20}_{-0.17} \pm 0.10$ | $\Upsilon(4S)$ → $\Upsilon(1S) \pi^+ \pi^-$ | $0.0019$ |
| $\Upsilon(1S) K^+ K^-$ | $0.061^{+0.016}_{-0.014} \pm 0.010$ | $0.067^{+0.017}_{-0.015} \pm 0.013$ | | |

resonance has been studied by Belle. Final states with two opposite-sign muons and two opposite-sign pions (or kaons) are selected. Signal candidates are identified using the kinematic variable $\Delta M$, defined as the difference between $M(\mu^+\mu^\mp \pi^+\pi^-)$ or $M(\mu^+\mu^-K^+K^-)$ and $M(\mu^+\mu^-)$ for pion or kaon modes.

The obtained branching fractions and partial widths are given in Table 1. For comparison, the partial widths for similar transitions from $\Upsilon(2S)$, $\Upsilon(3S)$, or $\Upsilon(4S)$ are also shown. The $\Upsilon(5S)$ partial widths (assuming that the signal events are solely due to the $\Upsilon(5S)$ resonance) are found to be in the range (0.52-0.85) MeV, that is more than 2 orders of magnitude larger than the corresponding partial widths for $\Upsilon(2S)$, $\Upsilon(3S)$, or $\Upsilon(4S)$ decays. The unexpectedly large $\Upsilon(5S)$ partial widths disagree with the expectation for a pure $b\bar{b}$ state, unless there is a new mechanism to enhance the decay rates.

3.2 Study of $\Upsilon(5S)$ decays to $B^0$ and $B^+$ mesons

The $\Upsilon(5S)$ decays to channels with $B^+$ and $B^0$ mesons are studied using the 23.6 fb$^{-1}$ data sample obtained at the $\Upsilon(5S)$ with the Belle detector. The reported results are preliminary. As discussed above, at the $\Upsilon(5S)$ energy a $b\bar{b}$ quark pair can be hadronized in various final states, such as two-body $B^0$ channels, two-body $B^{+0}$ channels, three-body channels $B\bar{B}\pi$, $B^*\pi$, $B^*\bar{B}\pi$, and four-body channel $B\bar{B}\pi\pi$. Generally a $b\bar{b}$ quark pair can also hadronize to a bottomonium state accompanied by $\pi$, $K$ or $\eta$ mesons.

The $B^+ \rightarrow J/\psi K^+$, $B^0 \rightarrow J/\psi K^{*0}$, $B^+ \rightarrow D^0\pi^+$ and $B^0 \rightarrow D^-\pi^+$ decays are fully reconstructed and treated simultaneously to measure the $B^+$ and $B^0$ production rates per $\bar{b}b$ event. The rates are $f(B^+) = (67.7 \pm 3.6 \pm 4.8)\%$ and $f(B^0) = (70.4^{+5.2}_{-5.1} \pm 6.2)\%$, with the average value of $f(B^{+0}) = (68.6^{+5.0}_{-5.0} \pm 5.0)\%$.

Assuming equal rates to $B^+$ and $B^0$ mesons in all channels produced at the $\Upsilon(5S)$ energy, we measure the fractions for $\bar{b}b$ event transitions to the two-body and multi-body channels with $B^{+0}$ meson pairs, $f(B\bar{B}) = (5.1 \pm 0.9 \pm 0.4)\%$, $f(B\bar{B} + B^*\bar{B}) = (12.6 \pm 1.2 \pm 1.0)\%$, $f(B^*\bar{B}^*) = (34.7 \pm 1.8 \pm 2.7)\%$, and $f(B^{(*)\bar{B}^{(*)}}(\pi(\pi)) = (17.0^{+1.6}_{-1.5} \pm 1.2)\%$. The two-body channel fractions are in a reasonable agreement with theoretical predictions. The multi-body channels are observed for the first time and the obtained fraction is unexpectedly large.

References

1. M. Artuso et al. (CLEO Collaboration), Phys. Rev. Lett. 95, 261801 (2005).
2. G. Bonvicini et al. (CLEO Collaboration), Phys. Rev. Lett. 96, 022002 (2006).
3. A. Drutskoy et al. (Belle Collaboration), Phys. Rev. Lett. 98, 052001 (2007).
4. A. Drutskoy et al. (Belle Collaboration), Phys. Rev. D 76, 012002 (2007).
5. C. Amsler et al. (Particle Data Group), Phys. Lett. B 667, 1 (2008).
6. R. Louvot et al. (Belle Collaboration), Phys. Rev. Lett. 102, 021801 (2008).
7. J. Wicht et al. (Belle Collaboration), Phys. Rev. Lett. 100, 121801 (2008).
8. K.-F. Chen et al. (Belle Collaboration), Phys. Rev. Lett. 100, 112001 (2008).