\( \Upsilon(5S) \) Results at Belle\(^1\)

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Abstract. The data sample recorded with the Belle detector at the KEKB B factory (Tsu kuba, Japan) operating at the \( \Upsilon(4S) \) energy provides interesting and new results about the \( B_s^0 \) mesons and the \( \Upsilon(5S) \) resonance. Recent analyses, based on data samples collected at the \( \Upsilon(5S) \) resonance (23.6 fb\(^{-1}\)) or near it (7.9 fb\(^{-1}\)), are presented with a special focus on the final results on the \( B_s^0 \rightarrow D_s^- \pi^+ \) and \( B_s^0 \rightarrow D_s^+ K^\pm \) decays, and on the intriguing \( \Upsilon(5S) \rightarrow \Upsilon(nS) \pi^+ \pi^- \) measurements.

The Belle experiment \([1]\), located at the interaction point of the KEKB asymmetric-energy \( e^+ e^- \) collider \([2]\), was designed for the study of \( B \) mesons created by \( e^+ e^- \) annihilation produced at a center-of-mass (CM) energy corresponding to the mass of the \( \Upsilon(4S) \) resonance \((\sqrt{s} \approx 10.58 \text{ GeV})\). After having recorded an unequaled sample of \( \approx 800 \text{ millions of } BB \) pairs\(^2\), the Belle collaboration started to record collisions at higher energies, opening the possibility to study other particles, like the poorly-known \( B_s^0 \) meson. Up to now, 23.6 fb\(^{-1}\) of data, containing \( \approx 2.8 \text{ millions of } B_s^0 \) mesons, have been analyzed at the energy of the \( \Upsilon(5S) \) resonance \((\sqrt{s} \approx 10.87 \text{ GeV})\).

The \( \Upsilon(5S) \) resonance is above the \( B_s^0 \bar{B}_s^0 \) threshold and it was naturally expected that the \( B_s^0 \) meson could be studied as well as the \( B \) mesons are studied with \( \Upsilon(4S) \) data. The large potential of such \( \Upsilon(5S) \) data was quickly confirmed \([3, 4]\) with the 2005 engineering run representing 1.86 fb\(^{-1}\). The main advantage with respect to the hadronic colliders is the possibility of measurements of absolute branching fractions. However, the abundance of \( B_s^0 \) mesons in \( \Upsilon(5S) \) hadronic events has to be precisely determined. Above the \( e^+ e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c} \) continuum events, the \( e^+ e^- \rightarrow b\bar{b} \) process can produce different kinds of final states: seven with a pair of non-strange \( B \) mesons \((B^+ B^-, B^* B, B B, B^* B\pi, B^* B\pi, B B\pi \text{ and } BB\pi\pi)\) and three with a pair of \( B_s^0 \) mesons \((B_s^0 B_s^+, B_s^+ B_s^- \text{ and } B_s^0 B_s^0)\) since the \( B^* \) and \( B_s^0 \) mesons always decay by emission of a photon. The total \( e^+ e^- \rightarrow b\bar{b} \) cross section at the \( \Upsilon(5S) \) energy was measured to be \( \sigma_{\Upsilon(5S)} = (302 \pm 14) \text{ pb} \) \([3, 5]\) and the fraction of \( B_s^0 \) events to be \( f_s = \sigma(e^+ e^- \rightarrow B_s^0 \bar{B}_s^0)/\sigma_{\Upsilon(5S)} = (19.3 \pm 2.9) \% \) \([6]\). The dominant \( B_s^0 \) production mode, \( b\bar{b} \rightarrow B_s^0 \bar{B}_s^0 \), represents approximately 90\% \([7]\) of the \( b\bar{b} \rightarrow B_s^{(*)} \bar{B}_s^{(*)} \) events. Published results on the \( B_s^0 \rightarrow D_s^- \pi^+ \) and \( B_s^0 \rightarrow D_s^+ K^\pm \) modes \([7]\) and on the electromagnetic penguin decays

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\(^2\) The notation “\( B \)” refers either to a \( B_s^0 \) or a \( B^+ \). Moreover, charge-conjugated states are implied everywhere.
$B_s^0 \rightarrow \phi \gamma$ and $B_s^0 \rightarrow \gamma \gamma$ [8] are presented. Preliminary results about the $B_s^0 \rightarrow J/\psi K_S^0$ and $B_s^0 \rightarrow J/\psi \phi$ modes [9] and the semi-leptonic $B_s^0$ decays [10] are also described. In addition, recent results on bottomonium production are reported [11], including preliminary measurements obtained with the data from the energy scan performed near the $\Upsilon(5S)$ resonance [12].

For the exclusive modes, the $B_s^0$ candidates are fully reconstructed from the final-state particles. The signal is analyzed with the successful method developed at the $B$ factories. From the reconstructed four-momentum in the CM ($E_{B_s^0}^*, p_{B_s^0}^*$), two variables are formed: the energy difference $\Delta E = E_{B_s^0}^* - \sqrt{s}/2$ and the beam-constrained mass $M_{bc} = \sqrt{s}/4 - p_{B_s^0}^2$. The signal yields are extracted from a two-dimensional fit performed of the distribution of these two variables. As the $B_s^0$ can be produced via three kinematically-different $\Upsilon(5S)$ decays\(^3\), we expect three signal regions in the $(M_{bc}, \Delta E)$ plane. The location of these regions (two observables per region) can be related to the $B_s^0$ and $B_s^0$ masses, providing a measurement of these two interesting physical parameters.

The flavour-specific $B_s^0 \rightarrow D_s^- \pi^+$ mode proceeds dominantly via a tree amplitude. Its Cabibbo-suppressed counterpart, $B_s^0 \rightarrow D_s^* K^\pm$, is not flavour-specific and is therefore interesting for $CP$-violation studies. The dominant $B_s^0 \rightarrow D_s^- \pi^+$ mode is a good candidate for a normalization channel at hadron colliders thanks to its clean signature (four charged tracks) and its large branching fraction. The $D_s^-$ mesons are reconstructed via three channels: $D_s^- \rightarrow \phi(K^+K^-)\pi^-$, $D_s^- \rightarrow K^*(0)(K^+\pi^-)K^-$ and $D_s^- \rightarrow K_S(\pi^+\pi^-)K^-$. The selected candidates are shown in Fig. 1.

**Figure 1.** $B_s^0 \rightarrow D_s^- \pi^+$ (top) and $B_s^0 \rightarrow D_s^+ K^\pm$ (bottom) candidates selected in 23.6 fb\(^{-1}\) and represented in the $(M_{bc}, \Delta E)$ plane. On the top plot, the three boxes represent the $2.5\sigma$ regions where $B_s^0$ candidates from $\Upsilon(5S) \rightarrow B_s^* B_s^*$, $B_s^* B^0_s$, $B^0_s B^0_s$ modes (from left to right) are expected. On the bottom plot, the solid box represents the signal region, while the dashed box shows the location of $B_s^0 \rightarrow D_s^- \pi^+$ decays when the pion is misidentified as a kaon; both boxes are for the $\Upsilon(5S) \rightarrow B_s^* B_s^*$ mode only.

From the fitted $B_s^0 \rightarrow D_s^- \pi^+$ yields and peak positions in the three signal regions, we measure six parameters: $B(B_s^0 \rightarrow D_s^- \pi^+) = [3.67^{+0.35}_{-0.33}(\text{stat.})^{+0.43}_{-0.42}(\text{syst.}) \pm 0.49(f_s)] \times 10^{-3}$, $f_{B_s^0 B_s^*} = N_{B_s^0 B_s^*}/N_{B_s^* B_s^*} = (90.1^{+3.8}_{-4.0} \pm 0.2)\%$, $f_{B_s^* B_s^*} = N_{B_s^* B_s^*}/N_{B_s^* B_s^*} = (7.3^{+3.3}_{-3.0} \pm 0.1)\%$, $f_{B_s^0 B^0_s} = N_{B_s^0 B^0_s}/N_{B_s^* B_s^*} = (2.6^{+2.6}_{-2.5})\%$, $m_{B_s^0} = (5364.4 \pm 1.3 \pm 0.7)\text{ MeV}/c^2$ and $m_{B_s^*} = (5416.4 \pm 0.4 \pm 0.5)\text{ MeV}/c^2$. For the $B_s^0 \rightarrow D_s^+ K^\pm$ candidates, we fit a signal only in the $B_s^* B_s^*$ region as 90% of the events are concentrated there. A $3.5\sigma$ evidence with $6.7^{+3.4}_{-2.7}$ events is obtained, leading to the branching fraction $B(B_s^0 \rightarrow D_s^+ K^\pm) = [2.4^{+1.2}_{-1.0}(\text{stat.}) \pm 0.3(\text{syst.}) \pm 0.3(f_s)] \times 10^{-4}$.

The dominant process leading to the $B_s^0 \rightarrow b \phi \gamma$ and $B_s^0 \rightarrow b \gamma \gamma$ decays is an electromagnetic radiative penguin diagram. The $b \rightarrow s \gamma$ transitions are an important test for the standard model

\(^3\) In this context, the notation “$\Upsilon(5S)$” stands for any produced $b \bar{b}$ pair, including non-resonant $b \bar{b}$ continuum since it is not distinguishable from the resonant $\Upsilon(5S)$ state.
We obtain the first observation (5.5σ) with \(18^{+6}_{-5}\) events (Fig. 2), leading to the branching fraction \(B(B_s^0 \to \phi \gamma) = (57^{+18}_{-15} \times 10^{-6})\). This is the first observation of a radiative \(B_s^0\) decay. We don’t have enough statistics to see a significant \(B_s^0 \to \gamma\gamma\) excess (Fig. 3). We set, at 90% C.L., an upper limit \(B(B_s^0 \to \gamma\gamma) < 8.7 \times 10^{-6}\), which is six times more stringent than the previous limit and only one order of magnitude larger than the SM prediction.

A search for the \(B_s^0 \to J/\psi \phi\) decay (and the Cabibbo-suppressed \(B_s^0 \to J/\psi K_S^0\) decay) has been performed (Fig. 4). The leading contribution comes from the colour-suppressed \(b \to c\bar{c}s\) (\(ccd\)) spectator diagram, but a penguin loop may also contribute. While no significant signal is seen for the \(B_s^0 \to J/\phi K_S^0\) mode, the observation of \(\sim 45\) events for the \(B_s^0 \to J/\psi \phi\) mode leads to the first absolute measurement of the branching fraction \(B(B_s^0 \to J/\psi \phi) = (1.15^{+0.28}_{-0.30}) \times 10^{-3}\).

The inclusive semi-leptonic branching fractions of the \(B_s^0\) meson have been measured thanks to its fast particle-antiparticle oscillation: by requiring events with a fully reconstructed \(D_s^- \to \phi(\to K^+K^-)\pi^-\) and a fast lepton with the same sign, only events with a \(B_s^0\) pair are selected. After a fit of the lepton CM momentum to disentangle primary and secondary leptons, the results obtained are \(B(B_s^0 \to X^+\ell^-\nu) = (10.9\pm1.0\pm0.9)\%\) and \(B(B_s^0 \to X^+\mu^-\nu) = (9.2\pm1.0\pm0.8)\%\). The average is \(B(B_s^0 \to X^+\ell^-\nu) = (10.2\pm0.8\pm0.9)\%,\) in good agreement with \(B(B^0 \to X^+\ell^-\nu)\) [6] which is expected to be very similar.

Not only \(B_s^0\) mesons can be studied with \(\Upsilon(5S)\) data. A search for bottomonium production (\(\Upsilon(nS),\ n = 1, 2, 3\), based on the full reconstruction of \(\Upsilon(5S) \to \Upsilon(nS)\left(\to \mu^+\mu^-\right)\pi^+\pi^-\) and \(\Upsilon(5S) \to \Upsilon(nS)\left(\to \mu^+\mu^-\right)K^+K^-\) decays, showed rates about two order of magnitude larger than expected from \(\Upsilon(4S)\) rates. A six-point energy scan near the \(\Upsilon(5S)\) resonance has been performed to study the variation of these rates as function of \(\sqrt{s}\). On Fig. 5, a clear difference
between the inclusive hadronic line shape ($m = 10865 \pm 8$ MeV/$c^2$, $\Gamma = 110 \pm 13$ MeV) and the exclusive bottomonium-production line shape ($m = 10889.6 \pm 2.3$ MeV/$c^2$, $\Gamma = 54.7^{+8.9}_{-7.0}$ MeV) can be seen. While the former is compatible with previous CLEO and CUSB measurements [13, 14], the latter is shifted by $(+24.6 \pm 8.3)$ MeV/$c^2$ and twice narrower. An interpretation could be a new $Y_0$ state with small production cross section and large branching fraction to the $\Upsilon(nS)\pi\pi$ final state. However the Babar collaboration has recently measured [15] an inclusive line shape with a width twice smaller than Belle. The result of an exclusive analysis by Babar would be very welcome to help clarifying the situation.

![Hadronic shape](image)

Figure 5. Hadronic production (top) and $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ cross section (bottom) as a function of $\sqrt{s}$. On the top plot, the grey dashed line is the shape of the $\Upsilon(5S)$ and $\Upsilon(6S)$ as present in Ref. [6]. On the bottom plot, the three sets of points, representing $\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$ (circle, blue), $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ (square, red) and $\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$ (triangle, green) data, are fitted with the same Breit-Wigner shape.

To conclude, all these studies demonstrate the great potential of the Belle dataset recorded at $\Upsilon(5S)$ energy. The sensitivity obtained for several $B_0^0$ modes allows many interesting measurements, from $B_0^0$ physical parameters to searches for new physics. Besides that, the intriguing measurements of the $\Upsilon(5S) \to \Upsilon(nS)h^+h^-$ channels open a new interest in bottomonium spectroscopy. So far, the full Belle sample has reached 65 fb$^{-1}$, and the KEKB collider will continue delivering collisions at the $\Upsilon(5S)$ energy during 2009. Of course, many more interesting results are expected with the full Belle $\Upsilon(5S)$ dataset.