\textbf{\Large \textit{\(\Upsilon(5S)\) Results at Belle}}\textsuperscript{1}

Remi Louvot

\textit{(on behalf of the Belle collaboration)}

Laboratoire de Physique des Hautes Énergies, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

E-mail: remi.louvot@epfl.ch

\textbf{Abstract.} The data sample recorded with the Belle detector at the KEKB \(B\) factory (Tsukuba, Japan) operating at the \(\Upsilon(5S)\) 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 \(B_s^0 \rightarrow D_s^+ K^\mp\) decays, and on the intriguing \(\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-\) measurements.

The Belle experiment \cite{1}, located at the interaction point of the KEKB asymmetric-energy \(e^+e^-\) collider \cite{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 (\(\sqrt{s} \approx 10.58\) GeV). After having recorded an unequal sample of \(\sim 800\) millions of \(B\bar{B}\) 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 \(\sim 2.8\) millions of \(B_s^0\) mesons, have been analyzed at the energy of the \(\Upsilon(5S)\) resonance (\(\sqrt{s} \approx 10.87\) 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 \cite{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 (\(B^+B^-, B^0\bar{B}^0, B^*B^+, B^*B^0, B^0\bar{B}^0, B\bar{B}\pi\) and \(BB\pi\)) and three with a pair of \(B_s^0\) mesons (\(B_s^0B^+_s, B_s^+B_s^0\) and \(B^0sB^0\)) 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 \(\sigma_{\Upsilon(5S)}^{B_s} = (302 \pm 14)\) pb \cite{5} \cite{6} and the fraction of \(B_s^0\) events to be \(f_s = \sigma(e^+e^- \rightarrow B_s^{(*)}\bar{B}_s^{(*)})/\sigma_{\Upsilon(5S)}^{B_s} = (19.3 \pm 2.9)\%\) \cite{7}. The dominant \(B_s^0\) production mode, \(b\bar{b} \rightarrow B_s^0B_s^0\), represents approximately 90\% \cite{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 \(B_s^0 \rightarrow D_s^0 K^\mp\) modes \cite{7} and on the electromagnetic penguin decays \(B_s^0 \rightarrow \phi\gamma\) and \(B_s^0 \rightarrow \gamma\gamma\) \cite{8} are presented. Preliminary results about the \(B_s^0 \rightarrow J/\psi K_s^0\) and

\textsuperscript{1} Proceedings of a presentation at the Lake Louise Winter Institute 2009 (Alberta, Canada), 16–21 February 2009.

\textsuperscript{2} The notation “\(B\)” refers either to a \(B^0\) or a \(B^+\). Moreover, charge-conjugated states are implied everywhere.
$B_s^0 \rightarrow J/\psi \phi$ 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 $(E^*_{B^0},p^*_{B^0})$, two variables are formed: the energy difference $\Delta E = E^*_{B^0} - \sqrt{s}/2$ and the beam-constrained mass $M_{bc} = \sqrt{s/4-p^*_{B^0}^2}$. 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 $\Upsilon(5S)$ decay,[9] 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, $B_s^0 \rightarrow D_s^0 K^\pm$, 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: $D_s^- \rightarrow \phi(\rightarrow K^+K^-)\pi^-$, $D_s^- \rightarrow K^{*0}(\rightarrow K^+\pi^-)K^-$ and $D_s^- \rightarrow K_s^0(\rightarrow \pi^+\pi^-)K^-$. The selected candidates are shown in Fig.[9]

From the fitted $B_s^0 \rightarrow D_s^- \pi^+$ yields and peak positions in the three signal regions, we measure six parameters: $B(B_s^0 \rightarrow D_s^- \pi^+) = [3.67^{+0.35}_{-0.33}\text{(stat.)}]^{+0.43}_{-0.42}\text{(syst.)} \pm 0.49(f_{s})] \times 10^{-3}$, $f_{B_s^0B_s^*} = N_{B_s^0B_s^*}/N_{B_s^0} = (90.1^{+3.8}_{-4.0} \pm 0.2)\%$, $f_{B_s^0} = N_{B_s^0B_s^*}/N_{B_s^0} = (7.3^{+3.3}_{-3.0} \pm 0.1)\%$, $f_{B_s^0B_{s}^{*}} = N_{B_{s}^{*}B_{s}^{*}}/N_{B_{s}^{*}B_{s}^{*}} = (2.6^{+2.6}_{-2.5})\%$, $m_{B_{s}^{*}} = (5364.4 \pm 1.3 \pm 0.7) \text{ MeV}/c^2$ and $m_{B_{s}^{*}} = (5416.4 \pm 0.4 \pm 0.5) \text{ MeV}/c^2$. For the $B_{s}^{0} \rightarrow D_{s}^{\mp}K^{\pm}$ candidates, we fit a signal only in the $B_{s}^{0}B_{s}^{*}$ 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 $\mathcal{B}(B_{s}^{0} \rightarrow D_{s}^{\mp}K^{\pm}) = [2.4^{+1.2}_{-1.0}\text{(stat.)}]\pm0.3\text{(syst.)} \pm 0.3(f_{s})] \times 10^{-4}$.

The dominant process leading to the $B_{s}^{0} \rightarrow \phi\gamma$ and $B_{s}^{0} \rightarrow \gamma\gamma$ decays is an electromagnetic radiative penguin diagram. The $b \rightarrow s\gamma$ transitions are an important test for the standard model (SM). We obtain the first observation (5.5$\sigma$) with $18^{+6}_{-5}$ events (Fig.[2]), leading to the branching

\[\text{[3] In this context, the notation “} \Upsilon(5S) \text{” stands for any produced } bb \text{ pair, including non-resonant } bb \text{ continuum since it is not distinguishable from the resonant } \Upsilon(5S) \text{ state.}\]
fraction $B(B_s^0 \to \phi \gamma) = (57^{+18+12}_{-15-11}) \times 10^{-6}$. 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.

Figure 2. Selected $B_s^0 \to \phi \gamma$ candidates. The box is the 2.5σ region where the signal is expected for the $\Upsilon(5S) \to B_s^0 \bar{B}_s^0$ mode.

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 $b \to c\bar{c}s$ ($cc\bar{d}$) 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 $B(B_s^0 \to J/\psi \phi) = (1.15^{+0.28}_{-0.30}) \times 10^{-3}$.

Figure 3. Selected $B_s^0 \to \gamma \gamma$ candidates. The box is the 2.5σ region where the signal is expected for the $\Upsilon(5S) \to B_s^0 \bar{B}_s^0$ mode.

Figure 4. Selected $B_s^0 \to J/\psi \phi$ candidates. The left (right) plot presents candidates with the $J/\phi$ decaying to electrons (muons). The elliptic regions have the same meaning as the boxes in the top plot of Fig. 1.

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 $B_s^0\bar{B}_s^0$ pair are selected. After a fit of the lepton CM momentum to disentangle primary and secondary leptons, the results obtained are $B(B_s^0 \to X^+ e^- \nu) = (10.9 \pm 1.0 \pm 0.9)\%$ and $B(B_s^0 \to X^+ \mu^- \nu) = (9.2 \pm 1.0 \pm 0.8)\%$. The average is $B(B_s^0 \to X^+ l^- \nu) = (10.2 \pm 0.8 \pm 0.9)\%$, in good agreement with $B(B^0 \to X^+ l^- \nu)$ [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 $\Upsilon(5S) \to \Upsilon(nS)(\to \mu^+\mu^-)\pi^+\pi^-$ and $\Upsilon(5S) \to \Upsilon(nS)(\to \mu^+\mu^-)K^+K^-$ 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 \((m = 10889.6 \pm 2.3 \text{ MeV}/c^2, \Gamma = 54.7^{+8.9}_{-7.6} \text{ MeV})\) can be seen. While the former is compatible with previous CLEO and CUSB measurements \([13, 14]\), the latter is shifted by \(+(24.6 \pm 8.3) \text{ MeV}/c^2\) and twice narrower. An interpretation could be a new \(Y_b\) state with small production cross section and large branching fraction to the \(\Upsilon(1S)\pi\pi\) 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.

To conclude, all these studies demonstrate the great potential of the Belle dataset recorded at \(\Upsilon(5S)\) energy. The sensitivity obtained for several \(B_s^0\) modes allows many interesting measurements, from \(B_s^0\) physical parameters to searches for new physics. Besides that, the intriguing measurements of the \(\Upsilon(5S) \rightarrow \Upsilon(nS)h^+h^-\) 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.

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

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

\[\text{[1] Abashian A et al. (Belle Collaboration) 2002 Nucl. Instrum. Methods A 479 117} \]
\[\text{[2] Kurokawa S and Kikutani E 2003 Nucl. Instrum. Methods A 499 1} \]
\[\text{[3] Drutskoy A et al. (Belle Collaboration) 2007 Phys. Rev. Lett. 98 052001} \]
\[\text{[4] Drutskoy A et al. (Belle Collaboration) 2007 Phys. Rev. D 76 012002} \]
\[\text{[5] Huang G S et al. (CLEO Collaboration) 2007 Phys. Rev. D 75 012002} \]
\[\text{[6] Amsler C et al. (Particle Data Group) 2008 Phys. Lett. B 667 1} \]
\[\text{[7] Louvot R et al. (Belle Collaboration) 2009 Phys. Rev. Lett. 102 021801} \]
\[\text{[8] Wicht J et al. (Belle Collaboration) 2008 Phys. Rev. Lett. 100 121801} \]
\[\text{[9] Piilonen L 2008 talk presented at the 34th International Conference on High Energy Physics, Philadelphia, Pennsylvania, USA} \]
\[\text{[10] Abe K et al. (Belle Collaboration) 2007 Belle-conf-0735, arXiv:0710.2548v1 [hep-ex]} \]
\[\text{[11] Chen K F et al. (Belle Collaboration) 2008 Phys. Rev. Lett. 100 112001} \]
\[\text{[12] Adachi I et al. (Belle Collaboration) 2008 Belle-conf-0861, arXiv:0808.2445v1 [hep-ex]} \]
\[\text{[13] Besson D et al. 1985 Phys. Rev. Lett. 54 381} \]
\[\text{[14] Lovelock D M J et al. 1985 Phys. Rev. Lett. 54 377} \]
\[\text{[15] Aubert B et al. (Babar Collaboration) 2009 Phys. Rev. Lett. 102 012001} \]