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Semileptonic B_s decays and Spectroscopy from the $\Upsilon(5S)$ at Belle

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This proceedings covers recent measurements of semileptonic B_s decays and bottomonium spectroscopy with data collected near the $\Upsilon(5S)$ resonance at Belle. The $\Upsilon(5S)$ data set comprises a total integrated luminosity of $121\,\mathrm{fb}^{-1}$, corresponding to $(7.1 \pm 1.3) \times 10^6$ $B_s^{(*)}\bar{B}_s^{(*)}$ pairs. This allows for the most precise determination of the $B_s \to X^- \ell^+ \nu_\ell$ branching fraction to date. The data sample has also been used for various novel results in bottomonium spectroscopy. I discuss the discovery of exotic Z_b states being a candidate for $B^*B^{(*)}$ molecules, the measurement of radiative $h_b(1,2P) \to \eta_b(1,2S)$ transitions including the first evidence for the $\eta_b(2S)$ state, a new production channel of $\Upsilon(1D)$, and the measurement of $\Upsilon(5S) \to \Upsilon(1,2S)\eta^{(\prime)}$ branching fractions.

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1. Introduction

The Belle experiment ran between 1999 and 2010 at the asymmetric e^+e^- collider KEKB in Tsukuba, Japan. More than 1 ab^{-1} of data were collected, mostly on the $\Upsilon(4S)$ resonance. The $\Upsilon(4S)$ resonance is a bottomonium state (quark content $b\bar{b}$) and is the ideal choice to study decays of B^0 and B^+ mesons as its mass is just a few MeV above the mass of a $B\bar{B}$ pair, which is its dominant decay channel ($> 96\%$) [1]. To study the more massive B_s meson, 121 fb^{-1} of data were collected at a higher centre of mass energy, near the $\Upsilon(5S)$ resonance. The Belle $\Upsilon(5S)$ data sample is unique in its size. However, only $(19.9 \pm 3.0)\%$ of the $\Upsilon(5S)$ decay to $B_s^{(*)}\bar{B}_s^{(*)}$ pairs while the majority decays to $B^{(*)}\bar{B}^{(*)}(\pi)$. There is also a small fraction, $(4.2^{+5.0}_{-0.6})\%$, decaying to lower bottomonium states [1]. The results presented here, from the Belle $\Upsilon(5S)$ data, comprise the determination of the $B_s \to X^-\ell^+\nu_\ell$ branching fraction and spectroscopy measurements of bottomonium states.

2. Inclusive semileptonic B_s decays

Semileptonic decays of b-flavoured mesons involve only one hadronic current and are well described by theory. They are a powerful tool to determine the magnitude of the elements of the Cabibbo-Kobayashi-Maskawa matrix V_{ub} and V_{cb}. The inclusive branching fraction $\mathscr{B}(B_s^0 \to X\ell\nu)$ plays also a key role in the estimation of the B_s production in LHC experiments and the B-factories [2]. These estimations are based on the equality of the semileptonic widths of b-flavoured mesons, motivated by $SU(3)$ flavour symmetry:

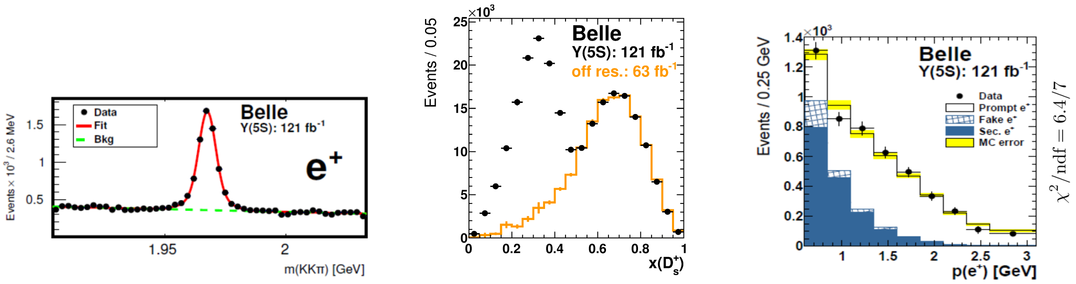
$$\Gamma_{sl}(B_s) = \Gamma_{sl}(B^+) = \Gamma_{sl}(B^0)\,. \tag{2.1}$$

Recent theory predicts that this equality relation holds at the level of 1% [3], which needs to be tested in experiment.

The presented measurement [4] uses the full Belle $\Upsilon(5S)$ data set containing $(7.1 \pm 1.3) \times 10^6$ $B_s^{(*)}\bar{B}_s^{(*)}$ pairs. One B_s is tagged reconstructing a D_s^+ meson from the Cabibbo-favoured $\bar{B}_s \to D_s^+X$ transition. The signal lepton ℓ^+ (e^+, μ^+) is studied in the decay of the other B_s in the event. By selecting same-sign charge combinations $D_s^+\ell^+$, it is guaranteed that the tag D_s^+ and the signal ℓ^+ stem from decays of different B_s^0 mesons. The inclusive semileptonic branching fraction can be extracted from the ratio of the efficiency corrected yields of $D_s^+\ell^+$ pairs and D_s^+ mesons, $N_{D_s^+\ell^+}$ and $N_{D_s^+}$, respectively. The extraction of the $B_s^0 \to X^-\ell^+\nu_\ell$ branching fraction takes into account the contamination from B decays using the known production and branching fractions, and the mixing of $B^0_{(s)}$ mesons.

The D_s^+ yield is determined from fits to the reconstructed D_s^+ mass distribution (Fig. 1(a)). Background from continuum processes $e^+e^- \to c\bar{c} \to D_sX$ is suppressed by rejecting high momentum D_s^+ candidates and the remaining background is estimated from 63 fb^{-1} of data collected below the threshold for open $B_{(s)}$ production (Fig. 1(b)). Secondary leptons (not from direct B_s^0 decays) and misreconstructed leptons are characterised by their lower momentum compared to signal leptons. A χ^2 fit to the lepton momentum spectrum obtained from D_s^+ mass fits serves to extract the signal lepton yield (Fig. 1(c)).

The result for the semileptonic branching fraction is $\mathscr{B}(B_s^0 \to X\ell\nu) = (10.6 \pm 0.5 \pm 0.7)\%$, in agreement with the theory expectation, and it significantly improves on the precision of the previous



(a) (b) (c)

Figure 1: Measurement of $\mathscr{B}(B_s^0 \to X\ell\nu)$ [4]: (a) Fit to the $KK\pi$ mass fit to the full $D_s^+e^+$ signal sample. (b) Spectrum of the normalised D_s^+ momentum $x(D_s^+)$ obtained from $KK\pi$ mass fits, D_s^+ sample. (c) Electron momentum spectrum obtained from $KK\pi$ mass fits, $D_s^+e^+$ sample.

measurement by BaBar[5]. The dominating systematic uncertainty (6%) is on the estimation of the B_s production near the $\Upsilon(5S)$. However, due to the D_s^+ tag this uncertainty is still small compared to the other measurements (15%) using untagged $\Upsilon(5S)$ samples.

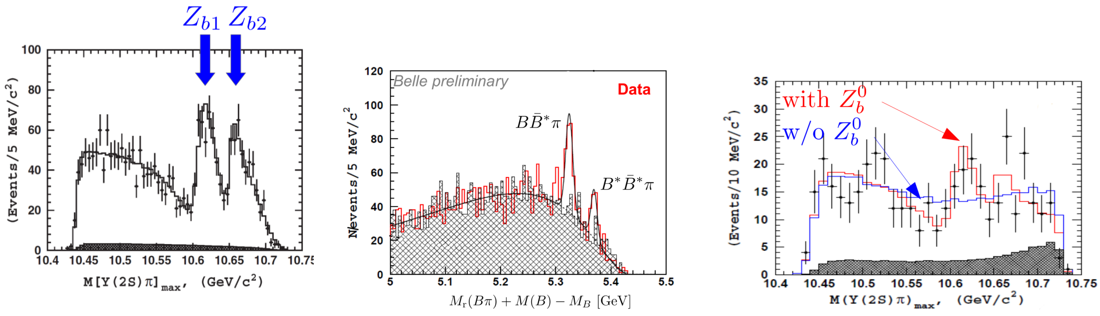
3. Discovery of charged and neutral Z_b states

A little zoo of new exotic states has been discovered in recent years at different experiments and different energies. A variety of interpretations for these states is proposed, e.g. molecules of mesons, tetraquarks or hadrocharmonia [6]. The presence of an exotic decay mechanism in $\Upsilon(5S)$ decays is suggested by the observed high rate of $\Upsilon(5S) \to h_b(mP)\pi^+\pi^-$ (m=1,2) transitions; this rate is expected to be suppressed compared to $\Upsilon(5S) \to Y(nS)\pi^+\pi^-$ (n=1,2,3) transitions because it requires a spin flip of one bottom quark [7]. Subsequent studies of $\Upsilon(5S)$ decays revealed the existence of two new charged states, $Z_b^+(10610)$ and $Z_b^+(10650)$. These studies make use of the known initial state at an e^+e^- collider to observe unreconstructed particles in the recoil mass distribution of the *recon*structed particles:

$$M_{\text{recon}}^{\text{mis}} = \sqrt{(E_{\text{beam}} - E_{\text{recon}})^2 - p_{\text{recon}}^2}\,, \tag{3.1}$$

where E_{beam} is half of the centre of mass energy, and all quantities are boosted to the centre of mass system of the colliding beams. This technique is not applicable in measurements at hadron colliders such as the LHC.

The Z_{b12}^+ signals are seen most directly in $M(\Upsilon(nS)\pi)_{\text{max}}$ distributions of exclusively reconstructed $\Upsilon(5S) \to \Upsilon(nS)[\mu^+\mu^-]\pi^+\pi^-$ decays (Fig. 2(a)). The 'max' refers to the choice of the $\Upsilon\pi$ combination with the higher invariant mass. The Dalitz analysis in the $M^2(\Upsilon(nS)\pi^\pm)_{\text{max}} \times M^2(\pi^+\pi^-)$ plane with non-resonant, Z_{b1}^+, Z_{b2}^+, $f_0(980)$ and $f_2(1270)$ components favours the quantum numbers $I^G(J^P) = 1^+(1^+)$. A more complex six dimensional Dalitz analysis supports this hypothesis. The study of the decays $\Upsilon(5S) \to Z_{b1,2}[h_b(mP)\pi^\mp]\pi^\pm$ applies the recoil mass technique twice: The $h_b(mP)$ yield is extracted from fits to the $M_{\pi\pi}^{\text{mis}}$ spectrum, which are performed in



(a)

(b)

(c)

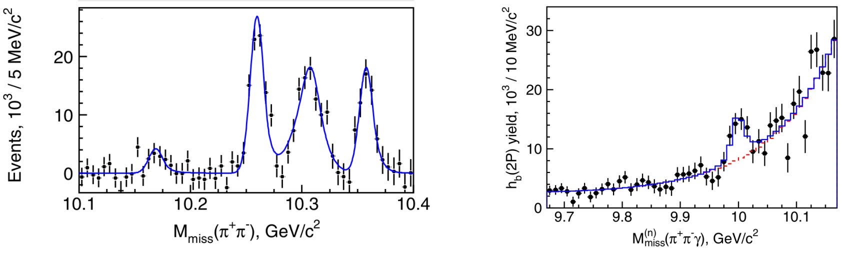
Figure 2: Discovery of the Z_b states; (a) $M(\Upsilon(2S)\pi)_{\max}$ spectrum in reconstructed $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ decays [8], (b) $M^{\rm mis}_{B\pi}$ spectrum of reconstructed $\Upsilon(5S) \to B\pi X$ decays [9], (c) $M(\Upsilon(2S)\pi)_{\max}$ distribution in reconstructed $\Upsilon(5S) \to \Upsilon(2S)\pi^0\pi^0$ decays [10].

bins of $M^{\rm mis}_{\pi}$, where the $Z^+_{b1,2}$ mass peaks can be observed. The measured masses and the widths of the Z^+_{b1} and Z^+_{b2} are in agreement for all channels. The averages are [8]:

$$\begin{aligned} Z^+_{b1}: &\quad M = (10607.2 \pm 2.0)\,\text{MeV} \quad \Gamma = (18.4 \pm 2.5)\,\text{MeV}\,, \\ Z^+_{b2}: &\quad M = (10652.2 \pm 1.5)\,\text{MeV} \quad \Gamma = (11.5 \pm 2.2)\,\text{MeV}\,. \end{aligned}$$

The observed masses of the new states are close to the mass of B^*B and B^*B^* pairs suggesting a molecular structure. Decays of $Z_{b1,2}$ to $B^{(*)}\bar{B}^*$ are observed in the analysis of $\Upsilon(5S) \to B\pi^\pm X$ events, where the B is a fully reconstructed B^+ or B^0 meson. The second B is detected in the recoil mass $M^{\rm mis}_{B\pi}$ distribution (Fig. 2(b)). The measured $\Upsilon(5S)$ decay modes with their branching fractions in brackets are: $BB\pi$ [$< 0.4\%$ at 90% confidence level], $BB^*\pi$ [$(2.83 \pm 0.29 \pm 0.46)\%$] and $B^*B^*\pi[(1.41 \pm 0.19 \pm 0.24)\%]$. The question if these decays proceed via intermediate Z_{b12} states is addressed in an amplitude analysis of the $M^{\rm mis}_{\pi}$ distributions in the B and B^* signal regions of $M^{\rm mis}_{B\pi}$. The $BB^*\pi$ sample is found to be described either by the sum of a Z^+_{b1} and a Z^+_{b2} component or Z^+_{b1} and a non-resonant component. The $B^*B^*\pi$ sample is well described by Z^+_{b2} alone or Z^+_{b2} with a non-resonant admixture. In all cases, a significant $Z_{b1,2}$ signal is found. Under the assumption that the only decay modes are to $\Upsilon(nS)\pi^+$, $h_b(mP)\pi^+$ and $B^{(*)}\bar{B}^*$, the Z^+_{b1} and Z^+_{b2} states decay dominantly to BB^* and B^*B^* pairs with branching fractions of $(86.0 \pm 3.6)\%$ and $(73.4 \pm 7.0)\%$, respectively [9].

The discovery of the charged Z^+_{b12} states triggered the search for the neutral partners in fully reconstructed decays $\Upsilon(5S) \to \Upsilon(nS)[\ell^+\ell^-]\pi^0[\gamma\gamma]\pi^0[\gamma\gamma]$, where $\Upsilon(2S)$ is additionally reconstructed in the $\Upsilon(1S)[\ell^+\ell^-]\pi^+\pi^-$ channel. The $\Upsilon(nS)$ yields are extracted from fits to the $M^{\rm mis}_{\pi^0\pi^0}$ distributions and the branching fractions $\mathscr{B}(\Upsilon(5S) \to \Upsilon(1S)\pi^0\pi^0) = (2.25 \pm 0.11 \pm 0.20) \times 10^{-3}$ and $\mathscr{B}(\Upsilon(5S) \to \Upsilon(1S)\pi^0\pi^0) = (3.79 \pm 0.24 \pm 0.49) \times 10^{-3}$ are obtained. A similar Dalitz analysis to that used in the charged Z^+_{b12} states is performed. In the $\Upsilon(1S)\pi^0\pi^0$ sample, no significant Z^0_{b12} signal is found, nor it can be excluded. In the $\Upsilon(2S)\pi^0\pi^0$ sample, a Z^0_{b1} signal is observed with a significance of 4.9σ; its mass is determined to be $(10609 \pm 8 \pm 6)\,$MeV consistent with the Z^+_{b1} mass. The Z_{b2} signal was not significant (2σ) [10].



(a) (b)

Figure 3: Study of $\Upsilon(5S) \to \pi^+\pi^- X$; (a) Distribution of the recoil mass of the two pions, after subtraction of the combinatorial background – the peaks from left to right correspond to $\Upsilon(1D)$, $h_b(2P)$, $\Upsilon(2S) \to \Upsilon(1S)$ and $\Upsilon(2S)$, (b) Yield of $h_b(2P)$ mass fits to the $M^{\text{mis}}_{\pi\pi}$ distribution in bins of $M^{\text{mis}\,(2)}_{\pi\pi\gamma}$ (see text) – the significance of the $\eta_b(2S)$ peak is 4.2σ. [11]

4. Observation of $h_b(mP) \to \eta_b(m'S)$ transisitons and first evidence for $\eta_b(2S)$

The $h_b(mP)$ states recently discovered at Belle [7] are expected to decay via $h_b(mP) \to \eta_b(m'P)\gamma$ with significant rates. The search for these radiative transitions [11] and the measurement of the $\eta_b(m'P)$ masses and widths use the production chain $\Upsilon(5S) \to Z^+_{b12}\pi^- \to h_b(mP)\pi^+\pi^-$. Only the two pions and the photon from the $h_b(mP)$ decay are reconstructed. Events are selected in the $Z^+_{b1,2}$ mass window of the M^{mis}_{π} distribution and the $h_b(mP)$ yield is determined from fits to the $M^{\text{mis}}_{\pi\pi}$ distribution (Fig. 3(a)). These fits are performed in bins of $M^{\text{mis}\,(m)}_{\pi\pi\gamma} = M^{\text{mis}}_{\pi\pi\gamma} - M^{\text{mis}}_{\pi\pi} - M(h_b(mP))$. This variable transformation removes the correlation of $M^{\text{mis}}_{\pi\pi}$ and $M^{\text{mis}}_{\pi\pi\gamma}$ in the signal region. Figure 3(b) shows the $\eta_b(2S)$ signal peak in the $M^{\text{mis}\,(2)}_{\pi\pi\gamma}$ distribution, and is the first evidence for this state. The observed transitions with the measured branching fractions given in brackets are: $h_b(1P) \to \eta_b(1S)\gamma$ $[(49.2 \pm 5.7^{+5.6}_{-3.3})\%]$, $h_b(2P) \to \eta_b(1S)\gamma$ $[(22.3 \pm 3.8^{+3.1}_{-3.3})\%]$, $h_b(2P) \to \eta_b(2S)\gamma$ $[(47.5 \pm 10.5^{+6.8}_{-7.7})\%]$. The extracted masses and widths of the $\eta_b(m'S)$ states are:

$$\begin{array}{lll} \eta_b(1S): & M = (9402.4 \pm 1.5 \pm 1.8)\,\text{MeV} & \Gamma = (10.8^{+4.0+4.5}_{-3.7-2.0})\,\text{MeV} \\ \eta_b(2S): & M = (9999.0 \pm 3.5^{+2.8}_{-1.9})\,\text{MeV} & \Gamma < 24\,\text{MeV} \quad [90\%\text{C.L.}] \end{array}$$

These quantities are particularly relevant to the hyperfine splitting $\Delta M_{\text{HF}}(mS) = M_{\Upsilon(mS)} - M_{\eta_b(mS)}$, which is a probe of the spin dependence of bound state energy levels, and puts constraints on theoretical descriptions of spin-spin interactions. The results are in agreement with lattice calculations [12, 6].

5. Study of the decays $\Upsilon(5S) \to \Upsilon(mS)\pi^+\pi^-\gamma\gamma$

A new production channel of the $\Upsilon(1D)$ state has been discovered in the decays $\Upsilon(5S) \to \Upsilon(1D)\pi^+\pi^-$ $\{\Upsilon(1D) \to \chi_{bi}\gamma,\ \chi_{bi} \to \Upsilon(1S)\gamma\}$. The $\Upsilon(1D)$ signal is observed in the $M^{\text{mis}}_{\pi\pi}$ distribution and the measured product of branching fractions is $\mathscr{B}(\Upsilon(5S) \to \Upsilon(1D)\pi^+\pi^-) \cdot \sum_{i=1,2} \mathscr{B}(\Upsilon(1D) \to \chi_{bi}\gamma) \cdot \mathscr{B}(\chi_{bi} \to \Upsilon(1S)\gamma) = [2.0 \pm 0.4] \times 10^{-4}$. The branching fractions of the decays $\Upsilon(5S) \to \Upsilon(mS)\eta^{(\prime)}$ were measured in the same sample with the results: $\Upsilon(1S)\eta$ $[(7.3 \pm 1.6) \times 10^{-4}]$, $\Upsilon(2S)\eta$ $[(38.1 \pm 4.2) \times 10^{-4}]$, $\Upsilon(1S)\eta'$ $[< 1.1 \times 10^{-4}$ (90% C.L.)].

6. Outlook

The presented analyses from the Belle $\Upsilon(5S)$ data set are a good example of the complementarity between the B factories and the LHC experiments. The key feature for the $B_s \to X^-\ell^+\nu$ branching fraction measurement is the production of $B_s\bar{B}_s$ pairs in $\Upsilon(5S)$ decays, while the complete knowledge of the $\Upsilon(5S)$ four-momentum, determined from the e^+e^- beam parameters, is the prerequisite for the recoil mass technique applied in the spectroscopy studies. The Belle II experiment, currently being constructed at SuperKEKB, will provide a significantly larger data set and open the possibility for new analysis strategies such as B_s tagging through full reconstruction of the second B_s in the event. There are also interesting prospects for spectroscopy measurements at a next generation B factory [13].

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