BLED WORKSHOPS IN PHYSICS
VOL. 14, NO. 1
p. 45

Proceedings of the Mini-Workshop
Looking into Hadrons
Bled, Slovenia, July 7 - 14, 2013

New results on quarkonium spectroscopy and exotic quarkonium-like resonances at B-factories*

Marko Petrič**

Jožef Stefan Institute, Ljubljana, Slovenia

Abstract. These proceedings covers recent results from spectroscopy measurements with data collected at the Belle experiment, which has been operating at the KEKB asymmetric e^+e^- collider at KEK in Tsukuba, Japan. The data sample can be used for various novel searches in spectroscopy. The paper discusses the discovery of exotic Z_b states, the measurement of radiative $h_b(1,2P) \to \eta_b(1,2S)$ transitions including the first evidence for the $h_b(2S)$ state, and the discovery of the charmed state $Z^+(3900)$.

1 Introduction

The Belle experiment [1] was taking data between 1999 and 2010 at the asymmetric e^+e^- collider KEKB [2] in Tsukuba, Japan. During this time more than 1 ab^{-1} of data was collected, mostly at the $\Upsilon(4S)$ resonance, but also on resonances $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(5S)$, as well as in the nearby continuum. The Belle detector was a large-solid-angle magnetic spectrometers that consisted of Drift Chambers, a silicon vertex detectors [3], an electromagnetic calorimeter and a superconducting solenoid that provided a 1.5 T magnetic field. The amount of collected experimental data and superb detector performance enables many interesting analyses, including searches for new hadronic states and studies of their properties. In this paper we will cover interesting spectroscopic measurements performed of charmonium(-like) and bottomonium(-like) states.

2 Discovery of charged and neutral Z_b states

In the past years a myriad of new exotic states has been discovered at different experiments and different energies. A broad selection of interpretations for these states is being proposed, e.g. molecules of mesons, tetraquarks or hadrocharmonia [4]. The observed high rate of $\Upsilon(5S) \to h_b(mP)\pi^+\pi^-$ $(m = 1, 2)$ decays, which is expected to be suppressed compared to $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ $(n = 1, 2, 3)$ decays, since it requires a spin flip of one bottom quark [5] is a clear sign of an exotic decay mechanism in $\Upsilon(5S)$ decays. Consequent studies of $\Upsilon(5S)$ decays have shown the existence of two new charged states, $Z_b^+(10610) \equiv Z_{b1}^+$

* Talk delivered by Marko Petrič
** on behalf of the Belle Collaboration

and $Z_b^+(10650) \equiv Z_{b2}^+$. These studies are based on the known initial energy at B-factories to observe unreconstructed particles in the recoil mass distribution of the reconstructed particles:

$$M_{miss}^{recoil} = \sqrt{((E_{beam} - E_{recon})^2 - p_{recon}^2} \quad ,$$

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 like the LHC. A direct observation of the Z^+

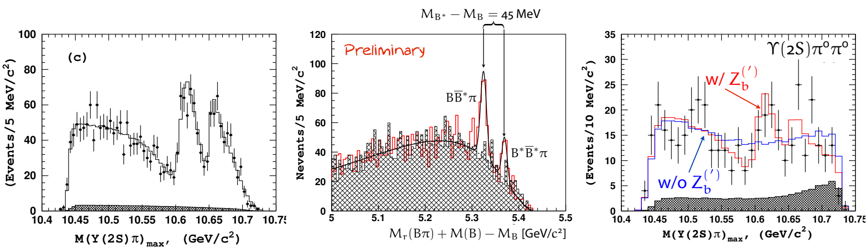

Fig. 1. Discovery of the Z_b states; (LEFT) $M(\Upsilon(2S)\pi)_{max}$ spectrum in reconstructed $\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$ decays [6], (MIDDLE) M_{mis} spectrum of reconstructed $\Upsilon(5S) \to B\pi X$ decays [7], (RIGHT) $M(\Upsilon(2S)\pi)_{max}$ distribution in reconstructed $\Upsilon(5S) \to \Upsilon(2S)\pi^0\pi^0$ decays [8].

signals is possible in the $M(\Upsilon(nS)\pi)_{max}$ distributions of exclusively reconstructed $\Upsilon(5S) \to \Upsilon(nS)[\mu^+\mu^-]\pi^+\pi^-$ decays (Figure 1). The subscript 'max' denotes the choice of the $\Upsilon\pi$ combination with the higher invariant mass. A Dalitz analysis with non-resonant Z_{b1}^+, Z_{b2}^+, $f_0(980)$ and $f_2(1270)$ components in the variables $M^2(\Upsilon(\pi S)\pi^+)_{max} \times M^2(\pi^+\pi^-)$ favours the quantum numbers $I^G(J^P) = 1^+(1^+)$. This hypothesis is supported by a more complex six dimensional Dalitz analysis. During the analysis of the decays $\Upsilon(5S) \to Z_{b1,2}[h_b(mP)\pi^\mp]\pi^\pm$ the recoil mass technique is applied twice: firstly the $h_b(mP)$ yield is determined from fits to the M_{mis} spectrum, which are performed in bins of M_{mis}, where the Z^+ 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 [6]:

$$\begin{aligned} Z_{b1}^+ &: \quad M = (10607.2 \pm 2.0)\mathrm{MeV}/c^2 \quad \Gamma = (18.4 \pm 2.5)\mathrm{MeV} \quad , \\ Z_{b2}^+ &: \quad M = (10652.2 \pm 1.5)\mathrm{MeV}/c^2 \quad \Gamma = (11.5 \pm 2.2)\mathrm{MeV} \quad . \end{aligned}$$

The observed new states have a mass close to the mass of B^*B and B^*B^* pairs suggesting a molecular structure. In the analyses of decays $\Upsilon(5S) \to B\pi^\pm X$ transitions of $Z_{b1,2}$ to $B^{(*)}\overline{B}^*$ are observed, where the B is a fully reconstructed B^+ or B^0 meson. The second B is measured in the recoil mass $M_{mis}^{B\pi}$ distribution (Figure 1). The determined branching fractions are $\mathcal{B}(\Upsilon(5S) \to BB\pi) < 0.60\%$ at 90% C. L., $\mathcal{B}(\Upsilon(5S) \to BB^*\pi) = (4.25 \pm 0.44 \pm 0.69)\%$ and $\mathcal{B}(\Upsilon(5S) \to B^*B^*\pi) = (2.12 \pm 0.29 \pm 0.36)\%$. To address the question if these decays proceed via the intermediate $Z_{b1,2}^+$ states an amplitude analysis of the M_{mis} distributions in the B and B^* signal regions of M_{mis} was made. It is found that the $BB^*\pi$ sample can be described by the sum of a Z_{b1}^+ and a Z_{b2}^+ component or Z_{b1}^+ and a non-resonant component. Whereas the $B^*B^*\pi$ sample is described well by a Z_{b2}^+ alone or a Z_{b2}^+ with a non-resonant admixture. A significant $Z_{b1,2}$ signal is found in all cases. Assuming that the only decay modes are to $\Upsilon(nS)\pi^+$, $h_b(mP)\pi^+$ and $B^*\overline{B}^*$ the Z_{b1}^+ and Z_{b2}^+ states decay predominantly to BB^* and B^*B^* pairs with branching fractions of $(86.0 \pm 3.6)\%$ and $(73.4 \pm 7.0)\%$, respectively [7].

The discovery of Z states prompted the search for their neutral counterparts in fully reconstructed decays $\Upsilon(5S) \to \Upsilon(nS)[\ell^+\ell^-]\pi^0\pi^0$, where $\Upsilon(2S)$ was additionally reconstructed in the $\Upsilon(1S)[\ell^+\ell^-]\pi^+\pi^-$ channel. From fits to the M_{mis} distributions the $\Upsilon(nS)$ yields are extracted and the resulting branching fractions are $B(\Upsilon(5S) \to \Upsilon(1S)\pi^0\pi^0) = (2.25 \pm 0.11 \pm 0.20) \times 10^3$, $B(\Upsilon(5S) \to \Upsilon(2S)\pi^0\pi^0) = (3.79 \pm 0.24 \pm 0.49) \times 10^3$ and $B(\Upsilon(5S) \to \Upsilon(3S)\pi^0\pi^0) = (2.09 \pm 0.24 \pm 0.34) \times 10^3$. As in the charged channel a Dalitz analysis is performed. No significant $Z_{b1,2}^0$ signal is found in the $\Upsilon(1S)\pi^0\pi^0$ sample, nor can it be excluded. However, a Z_{b1}^0 signal is observed with in the $\Upsilon(2S)\pi^0\pi^0$ sample (4.9σ) and the $\Upsilon(3S)\pi^0\pi^0$ sample (4.3σ); with the mass being $(10609 \pm 8 \pm 6)\text{MeV}/c^2$ which is consistent with the Z_{b1}^+ mass. The Z_{b2}^0 signal was not significant (2.9σ) [8].

3 Observation of $h_b(mP) \to \eta_b'(mS)$ transitions and first evidence for $\eta_b(2S)$

Belle has recently discovered the $h_b(mP)$ states [5] which are expected to decay significantly via $h_b(mP) \to \eta_b(m'P)\gamma$. This prompted the collaboration to search for these radiative transitions [9] and the measurement of the $\eta_b(m'P)$ masses and widths in the production chain $\Upsilon(5S) \to Z_{b1,2}^+\pi^- \to h_b(mP)\pi^+\pi^-$. In this analysis only two pions and the photon from the $h_b(mP)$ decay are reconstructed. Events with a $Z_{b1,2}^+$ are selected in the $Z_{b1,2}^+$ mass window of the M_{mis} distribution and the $h_b(mP)$ yield is determined from fits to the $M_{mis}^{\pi\pi}$ distribution (Figure 2). These fits are performed in bins of $M_{mis}^{\pi\pi\ (m)} = M_{mis}^{\pi\pi\gamma} - M_{mis}^{\pi\pi} - M(h_b(mP))$. With the help of this transformation correlation of $M_{mis}^{\pi\pi}$ and $M_{mis}^{\pi\pi\gamma}$ in the signal region are minimised. Figure 2 shows the $\eta(2S)$ signal peak in the $M_{mis}^{\pi\pi\gamma\ (2)}$ distribution, which is the first evidence for this state. The measured branching fractions are $\mathcal{B}(h_b(1P) \to \eta_b(1S)\gamma) = (49.2 \pm 5.7^{+5.6}_{-3.3})\%$, $\mathcal{B}(h_b(2P) \to \eta_b(1S)\gamma) = (22.3 \pm 3.8^{+3.1}_{-3.3})\%$, $\mathcal{B}(h_b(2P) \to \eta_b(2S)\gamma) = (47.5 \pm 10.5^{+6.8}_{-7.7})\%$. The extracted masses and widths of the $\eta_b(m'S)$ states are:

$$\begin{aligned} \eta_b(1S) \quad &: \quad M = (9402.4 \pm 1.5 \pm 1.8)\text{MeV}/c^2 \quad \Gamma = (10.8^{+4.0+4.5}_{-3.7-2.0})\text{MeV} \quad , \\ \eta_b(2S) \quad &: \quad M = (9999.0 \pm 3.5^{+2.8}_{-1.9})\text{MeV}/c^2 \quad \Gamma < 24\text{MeV} \quad . \end{aligned}$$

These results are needed for the calculation of the hyperfine splitting $\Delta M_{HF}(mS) = M_{\Upsilon(mS)} - M_{\eta_b(mS)}$, through which the spin dependence of bound state energy levels can be probed, and at the same time puts a constraint on theoretical descriptions of spin-spin interactions. The results are in agreement with lattice calculations [4,10].

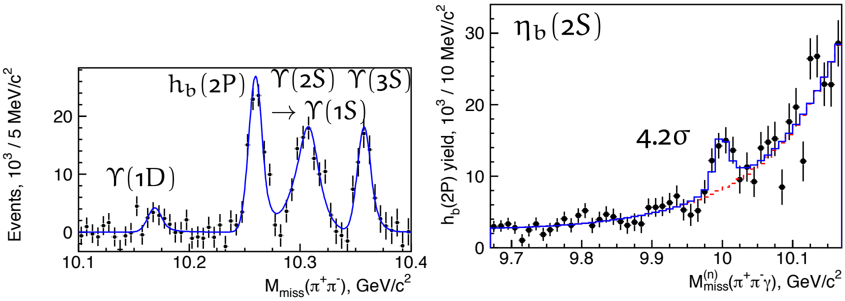

Fig. 2. Study of $\Upsilon(5S) \to \pi^+\pi^- X$; (Left) Distribution of the recoil mass of the two pions, after subtraction of the combinatorial background – the peaks from left to right correspond to $\Upsilon(1D)$, $h_b(2P)$, $\Upsilon(2S) \to \Upsilon(1S)$ and $\Upsilon(2S)$, (Right) Yield of $h_b(2P)$ mass fits to the M_{mis} distribution in bins of $M^{\pi\pi\gamma}_{miss}$ – the significance of the $\eta_b(2S)$ peak is 4.2σ [9].

4 Observation of a Charged Charmonium-like State $Z^+(3900)$

The Belle collaboration measured the cross section for $e^+e^- \to \pi^+\pi^- J/\psi$ between 3.8 GeV and 5.5 GeV on a data sample of 967 fb^{-1} [11]. In this analysis the $Y(4260)$ state is observed, and its resonance parameters are determined. Additionly, an excess of $\pi^+\pi^- J/\psi$ production around 4 GeV is observed, which

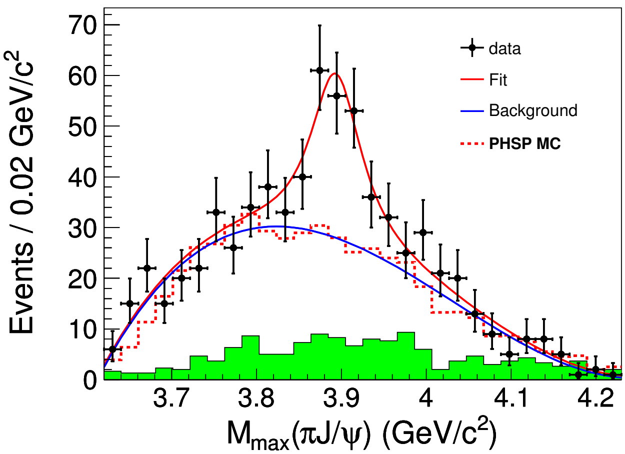

Fig. 3. Unbinned maximum likelihood fit to the distribution of the $M_{max}(\pi J/\psi)$. Points with error bars are data, the curves are the best fit, the dashed histogram is the phase space distribution and the shaded histogram is the non-$\pi^+\pi^- J/\psi$ background estimated from the normalized J/ψ sidebands [11].

was parametrized with a Breit-Wigner distribution and the results are consistent with the state $Y(4008)$ which was previously reported by Belle. In the subsequent Dalitz analysis of $Y(4260) \to \pi^+\pi^- J/\psi$ decays, the collaboration observes a structure is in the $M(\pi^{\pm} J/\psi)$ mass spectrum with 5.2σ significance, with mass $M = (3894.5 \pm 6.6 \pm 4.5)$ MeV/c^2 and width $\Gamma = (63 \pm 24 \pm 26)$ MeV/c^2 [11] (Figure 3). This structure can be interpreted as a new charged charmonium-like state. This state is close to the $D\overline{D}^*$ mass threshold; however, no enhancement is observed near the $D^*\overline{D}^*$ mass threshold. Since this Z state has a strong coupling to charmonium and is charged, it can be concluded that it cannot be a conventional $c\bar{c}$ state.

References

1. A. Abashian et al., Nucl. Instrum. Methods A **479**, 117 (2002).
2. S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods A **499** (2003).
3. Z. Natkaniec et al., Nucl. Instrum. Methods A **560**, 1 (2006).
4. N. Brambilla et al., Eur.Phys. J. C **71**, 1534 (2011).
5. I. Adachi et al. (Belle Collaboration), Phys. Rev. Lett. **108**, 032001 (2012).
6. A. Bondar et al. (Belle Collaboration), Phys. Rev. Lett. **108**, 122001 (2012).
7. I. Adachi et al. (Belle Collaboration), `arxiv:1209.6450[hep-ph]`.
8. I. Adachi et al. (Belle Collaboration), `arxiv:1207.4345[hep-ph]`.
9. R. Mizuk et al. (Belle Collaboration), Phys. Rev. Lett. **109**, 232002 (2012), `arxiv:1205.6351[hep-ph]`.
10. S. Meinel, Phys. Rev. D **82**, 114502 (2010).
11. Z. Liu et al. (Belle Collaboration), Phys. Rev. Lett. **110**, 252002 (2013).