

Status and new results on the Z_b resonances

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Recently Belle observed two charged bottomonium-like states, $Z_b(10610)$ and $Z_b(10650)$, that are produced in the $\Upsilon(5S) \rightarrow Z_b^\pm \pi^\mp$ transitions and that decay to $\Upsilon(nS)\pi^\pm$ ($n = 1, 2, 3$) and $h_b(mP)\pi^\pm$ ($m = 1, 2$) channels. The masses of these states are close to the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds, and their favored spin-parities are $J^P = 1^+$. We review status and new results on Z_b resonances, that include the observation of the $Z_b \rightarrow B^{(*)}\bar{B}^*$ decays and an evidence for the neutral member of the Z_b isotriplet. All properties of the Z_b states are consistent with their molecular interpretation.

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B-factories observed significant number of charmonium-like states with properties that do not fit the $c\bar{c}$ models. The first among these states was $X(3872)$, observed by Belle in 2003 [1]. Its mass is very close to the $D^0\bar{D}^{*0}$ threshold and its favored interpretation is a mixture of the conventional $\chi_{c1}(2P)$ charmonium with a $D\bar{D}^*$ molecule. Other anomalous XYZ states lie in the above threshold region; they are discussed in a separate talk at this meeting.

Recently Belle observed bottomonium-like states $Z_b(10610)$ and $Z_b(10650)$ with masses close to the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds, respectively [2]. Unlike $X(3872)$, these states are charged, i.e. their quark content is explicitly exotic, e.g. $|b\bar{b}u\bar{d}\rangle$. We review the status and the most recent results on Z_b , including the Z_b decays to the $B\bar{B}^*$ and $B^*\bar{B}^*$ channels and an evidence for their neutral isospin partner Z_b^0 .

1. Observation of Z_b states in the $\Upsilon(nS)\pi^+\pi^-$ and $h_b(mP)\pi^+\pi^-$ channels

Recently Belle observed the $h_b(1P)$ and $h_b(2P)$ states in the transitions $\Upsilon(5S) \rightarrow h_b(mP)\pi^+\pi^-$ [3]. The rates of these transitions appeared to be unsuppressed relative to the $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-$ ($n=1,2,3$). The $h_b(mP)$ production involves spin-flip of b -quark and is suppressed as $(\Lambda_{QCD}/m_b)^2$ in the multipole expansion; this unexpected result motivated further studies of the $h_b(mP)$ and $\Upsilon(nS)$ production mechanisms.

Belle studied the resonant structure of the $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-$ and $h_b(mP)\pi^+\pi^-$ decays ($n=1,2,3$; $m=1,2$) [2]. The $\Upsilon(nS)$ [$h_b(mP)$] states are reconstructed in the $\mu^+\mu^-$ channel [inclusively using missing mass of the $\pi^+\pi^-$ pairs]. Invariant mass spectra of the $\Upsilon(nS)\pi^\pm$ and $h_b(mP)\pi^\pm$ combinations are shown in Fig. 1. Each distribution shows two peaks. For the channels

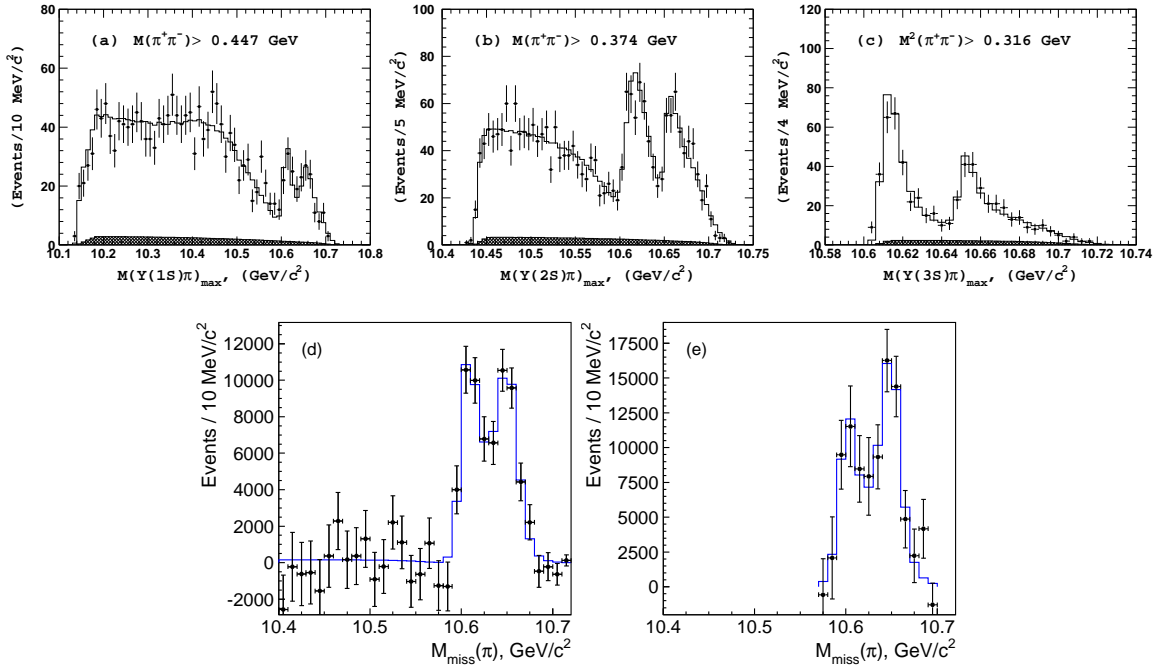


Figure 1: Invariant mass spectra of the (a) $\Upsilon(1S)\pi^\pm$, (b) $\Upsilon(2S)\pi^\pm$, (c) $\Upsilon(3S)\pi^\pm$, (d) $h_b(1P)\pi^\pm$ and (e) $h_b(2P)\pi^\pm$ combinations.

$\Upsilon(nS)\pi^+\pi^-$ [$h_b(mP)\pi^+\pi^-$] the Dalitz plot analysis [fit to one-dimensional distributions] is performed. The non-resonant contributions in the $h_b(mP)\pi^+\pi^-$ channels are negligible, justifying the one-dimensional analysis. Preliminary results of the angular analysis indicate that both states have the same spin-parity $J^P = 1^+$ [4], therefore coherent sum of Breit-Wigner amplitudes is used to describe the signals. The Dalitz plot model includes also the $\pi^+\pi^-$ resonances $f_0(980)$ and $f_2(1270)$, and non-resonant contribution, parameterized as $a + bM_{\pi^+\pi^-}^2$, where a and b are complex numbers floating in the fit. The masses and widths of the two peaks are found to be in good agreement among different channels (see Fig. 2). Averaged over the five decay channels parameters are

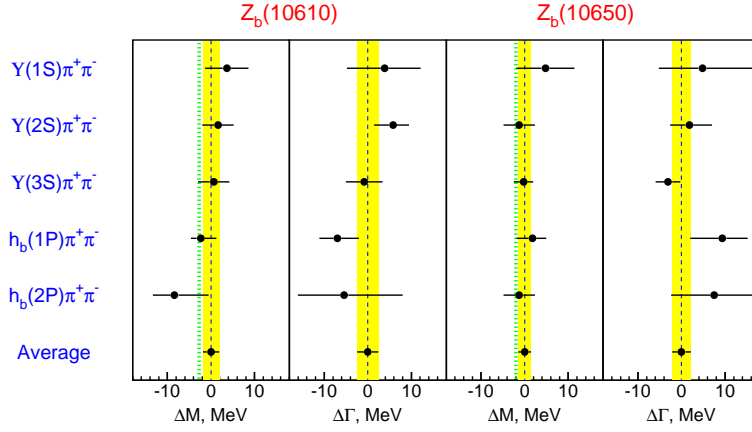


Figure 2: The deviations of the mass and width measurements of the $Z_b(10610)$ and $Z_b(10650)$ in different channels from the averaged over all channels value. Green vertical lines indicate the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds.

$$\begin{aligned} M_1 &= (10607.4 \pm 2.0) \text{ MeV}/c^2, & M_2 &= (10652.2 \pm 1.5) \text{ MeV}/c^2, \\ \Gamma_1 &= (18.4 \pm 2.4) \text{ MeV}, & \Gamma_2 &= (11.5 \pm 2.2) \text{ MeV}. \end{aligned}$$

The peaks are identified as signals of two new states, named $Z_b(10610)$ and $Z_b(10650)$.

Another result of the amplitude analyses is that the phase between the $Z_b(10610)$ and $Z_b(10650)$ amplitudes is zero for the $\Upsilon(nS)\pi^+\pi^-$ channels, and 180° for the $h_b(mP)$ channels.

The masses of the $Z_b(10610)$ and $Z_b(10650)$ states are close to the $B\bar{B}^*$ and $B^*\bar{B}^*$ thresholds, respectively. All the properties of the $Z_b(10610)$ and $Z_b(10650)$ find natural explanation once molecular structure for these states is assumed without even the need of dynamic model. Considering the heavy-quark spin structure of the $B^{(*)}\bar{B}^*$ molecule with appropriate quantum numbers, one concludes that Z_b contain both ortho- and para-bottomonium components [5]. The weight of these components is equal, therefore the decay to the $h_b(mP)\pi^\pm$ is not suppressed relative to the $\Upsilon(nS)\pi^\pm$. The $Z_b(10610)$ and $Z_b(10650)$ differ by the sign between ortho- and para-bottomonium components, this explains why the $Z_b(10610)$ and $Z_b(10650)$ amplitudes appear with the sign plus for the $\Upsilon(nS)\pi^+\pi^-$ channels and with the sign minus for the $h_b(mP)\pi^+\pi^-$ channels. In the limit of infinitely heavy b quark the B and B^* mesons have equal mass, thus the $Z_b(10610)$ and $Z_b(10650)$ are also degenerate. Given minus sign between the Z_b amplitudes in the $h_b(mP)\pi^+\pi^-$ channel the contribution of this channel vanishes if the heavy quark symmetry is exact.

2. Observation of the $Z_b(10610) \rightarrow B\bar{B}^*$ and $Z_b(10650) \rightarrow B^*\bar{B}^*$ decays

Given proximity to the thresholds and finite widths, it is natural to expect that the rates of the “fall-apart” decays $Z_b(10610) \rightarrow B\bar{B}^*$ and $Z_b(10650) \rightarrow B^*\bar{B}^*$ are substantial in the molecular picture. To search for these transitions Belle studied the $\Upsilon(5S) \rightarrow [B^{(*)}\bar{B}^*]^\pm \pi^\mp$ decays [6]. One B meson is reconstructed fully using the $D^{(*)}\pi^+$ and $J/\psi K^{(*)}$ channels. The distribution of the missing mass of the $B\pi^\pm$ pairs shows clear signals of the $\Upsilon(5S) \rightarrow [B\bar{B}^*]^\pm \pi^\mp$ and $\Upsilon(5S) \rightarrow [B^*\bar{B}^*]^\pm \pi^\mp$ decays [see Fig. 3 (a)]; corresponding branching fractions of $(2.83 \pm 0.29 \pm 0.46)\%$

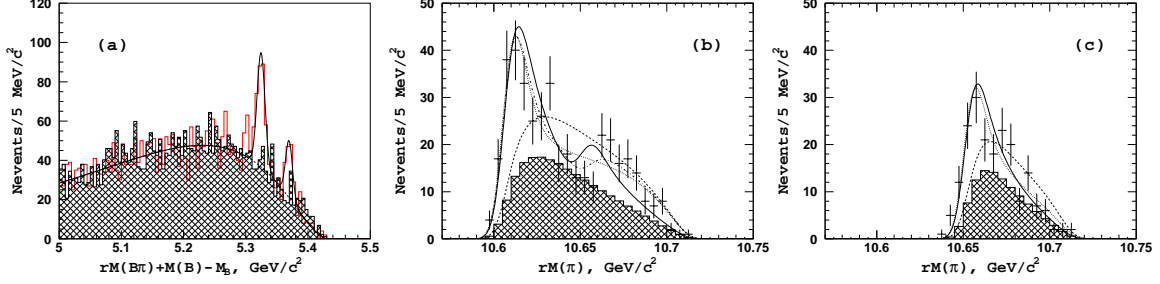


Figure 3: Missing mass of the pairs formed from the reconstructed B candidate and charged pion (a) and missing mass of the charged pions for the $B\pi$ combinations for (b) $\Upsilon(5S) \rightarrow B\bar{B}^*\pi$ and (c) $\Upsilon(5S) \rightarrow B^*\bar{B}^*\pi$ candidate events.

and $(1.41 \pm 0.19 \pm 0.24)\%$, respectively, are in agreement with previous Belle measurement [7]. No signal of the $\Upsilon(5S) \rightarrow [B\bar{B}]^\pm \pi^\mp$ decay is found, with upper limit on its fraction of $< 0.4\%$ at 90% confidence level.

The distributions in the $B\bar{B}^*$ and $B^*\bar{B}^*$ invariant mass for the $\Upsilon(5S) \rightarrow [B\bar{B}^*]^\pm \pi^\mp$ and $\Upsilon(5S) \rightarrow [B^*\bar{B}^*]^\pm \pi^\mp$ signal regions, respectively, indicate clear excess of events over background, peaking at the thresholds [see Fig. 3 (b) and (c)]. These threshold peaks are interpreted as the signals of the $Z_b(10610) \rightarrow B\bar{B}^*$ and $Z_b(10650) \rightarrow B^*\bar{B}^*$ decays, with significances of 8σ and 6.8σ , respectively. Despite much larger phase-space, no significant signal of the $Z_b(10650) \rightarrow B\bar{B}^*$ decay is found.

Assuming that the Z_b decays are saturated by the channels so far observed, Belle calculated relative branching fractions of the $Z_b(10610)$ and $Z_b(10650)$ (see Table 1). The $B^{(*)}\bar{B}^*$ channel

Table 1: Branching fractions (\mathcal{B}) of $Z_b(10610)$ and $Z_b(10650)$ assuming that the observed so far channels saturate their decays.

Channel	\mathcal{B} of $Z_b(10610)$, %	\mathcal{B} of $Z_b(10650)$, %
$\Upsilon(1S)\pi^+$	0.32 ± 0.09	0.24 ± 0.07
$\Upsilon(2S)\pi^+$	4.38 ± 1.21	2.40 ± 0.63
$\Upsilon(3S)\pi^+$	2.15 ± 0.56	1.64 ± 0.40
$h_b(1P)\pi^+$	2.81 ± 1.10	7.43 ± 2.70
$h_b(2P)\pi^+$	2.15 ± 0.56	14.8 ± 6.22
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	86.0 ± 3.6	–
$B^{*+}\bar{B}^{*0}$	–	73.4 ± 7.0

is dominant and accounts for about 80% of the Z_b decays. The $Z_b(10650) \rightarrow B\bar{B}^*$ channel is not

included in the table because its significance is marginal. If considered, the $Z_b(10650) \rightarrow B\bar{B}^*$ branching fraction would be $(25.4 \pm 10.2)\%$. All other fractions would be reduced by a factor of 1.33.

3. Evidence for neutral isotriplet member $Z_b(10650)^0$

Both $Z_b(10610)$ and $Z_b(10650)$ are isotriplets with only charged components observed originally. Belle searched for their neutral components using the $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^0\pi^0$ ($n = 1, 2$) decays [8]. These decays are observed for the first time and the measured branching fractions $\mathcal{B}[\Upsilon(5S) \rightarrow \Upsilon(1S)\pi^0\pi^0] = (2.25 \pm 0.11 \pm 0.22) \times 10^{-3}$ and $\mathcal{B}[\Upsilon(5S) \rightarrow \Upsilon(2S)\pi^0\pi^0] = (3.66 \pm 0.22 \pm 0.48) \times 10^{-3}$, are in agreement with isospin relations.

Belle performed the Dalitz plot analyses of the $\Upsilon(5S) \rightarrow \Upsilon(1S, 2S)\pi^0\pi^0$ transitions using the same model as for the charged pion channels (see Fig. 4). The $Z_b(10610)^0$ signal is found in

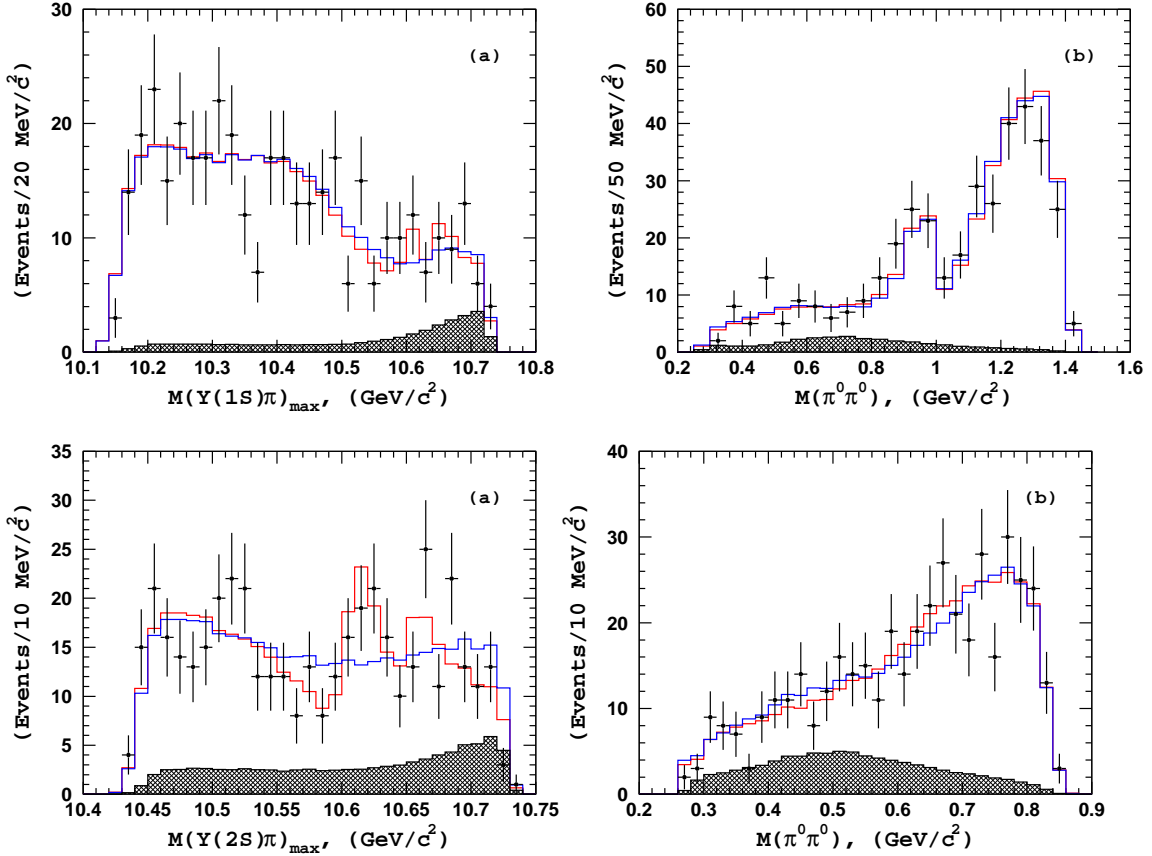


Figure 4: The projections of the Dalitz plot fit for the $\Upsilon(1S)\pi^0\pi^0 p$ (top row) and $\Upsilon(2S)\pi^0\pi^0$ (bottom row) channels on the $\Upsilon(nS)\pi^0$ (left column) and $\pi^0\pi^0$ invariant mass.

the $\Upsilon(2S)\pi^0$ channel with the significance of 4.9σ including systematics. The $Z_b(10610)^0$ mass of $(10609^{+8}_{-6} \pm 6)\text{MeV}/c^2$ is consistent with the charged $Z_b(10610)^\pm$ mass. The signal of the $Z_b(10610)^0$ in the $\Upsilon(1S)\pi^0$ channel and the $Z_b(10650)^0$ signal are insignificant. The Belle data do

not contradict the existence of the $Z_b(10610)^0 \rightarrow \Upsilon(1S)\pi^0$ and the $Z_b(10650)^0$, but the available statistics are insufficient to establish these signals.

4. Interpretations

As discussed at the end of Section 2, the assumption of molecular $B^{(*)}\bar{B}^*$ structure naturally explains all observed so far properties of the Z_b states. Their dynamical model, however, is an open question. Proposed interpretations include presence of the compact tetraquark [9], non-resonant rescattering [10], multiple rescatterings that result in the amplitude pole known as coupled channel resonance [11] and deuteron-like molecule bound by meson exchanges [12]. All these mechanisms (except for the tetraquark) are intimately related and correspond rather to quantitative than to qualitative differences. Further experimental and theoretical studies are needed to clarify the nature of the Z_b states.

As discussed in Ref. [5], based on heavy quark symmetry one can expect more states with similar nature but with differing quantum numbers. Such states should be accessible in radiative and hadronic transitions in data samples with high statistics at and above the $\Upsilon(5S)$, that will be available at the SuperKEKB.

5. Summary

Despite observed only recently, the Z_b states provide a very rich phenomenological object with a lot of experimental information available. They could be very useful for understanding dynamics of the hadronic systems near and above the open flavor thresholds.

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