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News from Belle: Recent Spectroscopy Results

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Abstract. This paper reports on some of the latest spectroscopic measurements performed with the experimental data collected by the Belle spectrometer, which has been operating at the KEKB asymmetric-energy e^+e^- collider in the KEK laboratory in Tsukuba, Japan.

1 Introduction

The Belle detector [1] at the asymmetric-energy e^+e^- collider KEKB [2] has accumulated about 1 ab^{-1} of data by the end of its operation in June 2010. The KEKB collider, called a *B-factory*, most of the time operated near the $\Upsilon(4S)$ resonance, but it has accumulated substantial data samples also at other Υ resonances, like $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(5S)$, as well as in the nearby continuum. In particular, the data samples at the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances are by far the largest available in the world, corresponding to integrated luminosities of 798 fb^{-1} and 123 fb^{-1}, respectively. Large amount of collected experimental data and excellent detector performance enabled many interesting spectroscopic results, including discoveries of new hadronic states and studies of their properties. This report covers most recent and interesting spectroscopic measurements—performed with either charmonium(-like) and bottomonium(-like) states.

2 Bottomonium and Bottomonium-like States

The Belle collaboration used a data sample at the CM energy around the $\Upsilon(5S)$ mass 10.89 GeV, and found large signals for decays into $\pi^+\pi^-\Upsilon(1S)$, $\pi^+\pi^-\Upsilon(2S)$ and $\pi^+\pi^-\Upsilon(3S)$ final states [3]. If these transitions are only from the $\Upsilon(5S)$ resonance, then the corresponding partial widths are more than two orders of magnitude larger than the corresponding partial widths for $\Upsilon(4S)$, $\Upsilon(3S)$ and $\Upsilon(2S)$ decays to $\pi^+\pi^-\Upsilon(1S)$. These results motivate a search for the $h_b(mP)$ resonances in the $\Upsilon(5S)$ data. $h_b(1P)$ and $h_b(2P)$ states are observed in the missing mass spectrum of $\pi^+\pi^-$ pairs for the $\Upsilon(5S)$ decays, with significances of 5.5σ and 11.2σ, respectively [4]. This is the first observation of the $h_b(1P)$ and $h_b(2P)$ spin-singlet bottomonium states in the reaction $e^+e^- \to h_b(mP)\pi^+\pi^-$ at the $\Upsilon(5S)$ energy. Later $h_b(1P)$ and $h_b(2P)$ were studied in the $\Upsilon(5S) \to h_b\pi^+\pi^- \to \gamma\eta_b(1S)\pi^+\pi^-$

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Decay mode	Branching fraction in %
$h_b(1P) \to \gamma\eta_b(1S)$	$49.2{\pm}5.7^{+5.6}_{-3.3}$
$h_b(2P) \to \gamma\eta_b(1S)$	$22.3{\pm}3.8^{+3.1}_{-3.3}$
$h_b(2P) \to \gamma\eta_b(2S)$	$47.5{\pm}10.5^{+6.8}_{-7.7}$

Table 1. The branching fractions for $h_b \to \gamma\eta_b$ decays, as measured by Belle.

decay [5]. In the same final state, Belle observes [5] also the first evidence for a $\eta_b(2S)$ in $\Upsilon(5S) \to h_b(2P)\pi^+\pi^- \to \gamma\eta_b(2S)\pi^+\pi^-$ decay. The width of $\eta_b(2S)$ is small, with $\Gamma = (4{\pm}8)$ MeV. Branching fractions for observed radiative h_b decays are summarized in Table 1.

Comparable rates of $h_b(1P)$ and $h_b(2P)$ production indicate a possible exotic process that violates heavy quark spin-flip and this motivates a further study of the resonant structure in $\Upsilon(5S) \to h_b(mP)\pi^+\pi^-$ and $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ decays [6]. Due to the limited statistics, only the study of $M(h_b(mP)\pi)$ distribution is possible for $h_b(mP)\pi^+\pi^-$, while in the case of $\Upsilon(nS)\pi^+\pi^-$ decay modes the Dalitz plot analysis can be performed. As a result, two charged bottomonium-like resonances, $Z_b(10610)$ and $Z_b(10650)$, are observed with signals in five different decay channels, $\Upsilon(nS)\pi^\pm$ $(n = 1, 2, 3)$ and $h_b(mP)\pi^\pm$ $(m = 1, 2)$. The averaged values for the mass and widths of the two states are calculated to be: $M(Z_b(10610)) = (10607.2 \pm 2.0)$ MeV, $\Gamma(Z_b(10610)) = (18.4 \pm 2.4)$ MeV and $M(Z_b(10650)) = (10652.2 \pm 1.5)$ MeV, $\Gamma(Z_b(10650)) = (11.5 \pm 2.2)$ MeV. The measured masses are only a few MeV above the thresholds for the open beauty channels $B^*\overline{B}$ (10604.6 MeV) and $B^*\overline{B}^*$ (10650.2 MeV) [9], which could indicate a molecular nature of the two observed states. Angular analysis of charged pion distributions favours the $J^P = 1^+$ spin-parity assignment for both $Z_b(10610)$ and $Z_b(10650)$.

3 Charmonium and Charmonium-like States

There has been a renewed interest in charmonium spectroscopy since 2002. The attention to this field was drawn by the discovery of the two missing $c\overline{c}$ states below the open-charm threshold, $\eta_c(2S)$ and $h_c(1P)$ [7,8] with J^{PC}=0^{-+} and 1^{+-}, respectively, but even with the discoveries of new new charmonium-like states (so called "XYZ" states).

3.1 The $X(3872)$ news

The storyabout the so called "XYZ" states began in 2003, when Belle reported on $B^+ \to K^+J/\psi\pi^+\pi^-$ analysis, where a new state decaying to $J/\psi\pi^+\pi^-$ was discovered [10]. The new state, called X(3872), was soon confirmed and also intensively studied by the CDF, DØ and *BABAR* collaborations [11–19]. So far it has been established that this narrow state ($\Gamma = (3.0^{+1.9}_{-1.4} \pm 0.9)$ MeV) has a mass of

(3872.2 ± 0.8) MeV, which is very close to the $D^0\overline{D}^{*0}$ threshold [9]. The intensive studies of several $X(3872)$ production and decay modes suggest two possible J^{PC} assignments, 1^{++} and 2^{-+}, and establish the $X(3872)$ as a candidate for a loosely bound $D^0\overline{D}^{*0}$ molecular state. However, results provided substantial evidence that the $X(3872)$ state must contain a significant $c\overline{c}$ component as well.

Recently, Belle performed a study of $B \to (c\overline{c}\gamma)K$ using the final data sample with 772 million of $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance [20]. Pure $D^0\overline{D}^{*0}$ molecular model [21] predicts $\mathcal{B}(X(3872) \to \psi'\gamma)$ to be less than $\mathcal{B}(X(3872) \to J/\psi\gamma)$. Results by the *BABAR* collaboration [19] show that $\mathcal{B}(X(3872) \to \psi'\gamma)$ is almost three times that of $\mathcal{B}(X(3872) \to J/\psi\gamma)$, which is inconsistent with the pure molecular model, and can be interpreted as a large $c\overline{c} - D^0\overline{D}^{*0}$ admixture. We observe $X(3872) \to J/\psi\gamma$ together with an evidence for $\chi_{c2} \to J/\psi\gamma$ in $B^\pm \to J/\psi\,\gamma K^\pm$ decays, while in our search for $X(3872) \to \psi'\gamma$ no significant signal is found. We also observe $B \to \chi_{c1}K$ decays in both, charged as well as neutral B decays. The obtained results suggest that the $c\overline{c}$-$D^0\overline{D}^{*0}$ admixture in $X(3872)$ may not be as large as discussed above.

New results for the $X(3872) \to J/\psi\pi^+\pi^-$ decay modes in $B^+ \to K^+X(3872)$ and $B^0 \to K^0\ (\to\pi^+\pi^-)X(3872)$ decays are obtained with the complete Belle data set of 772 million $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance [22]. The results for the $X(3872)$ mass and width are obtained by a 3-dimensional fit to distributions of the three variables: beam-constrained-mass $M_{bc}= \sqrt{(E_{beam}^{cms})^2 - (p_B^{cms})^2}$ (with the beam energy E_{beam}^{cms} and the B-meson momentum p_B^{cms} both measured in the centre-of-mass system), the invariant mass $M_{inv}(J/\psi\pi^+\pi^-)$ and the energy difference $\Delta E = E_B^{cms} - E_{beam}^{cms}$ (where E_B^{cms} is the B-meson energy in the centre-of-mass system). As a first step, the fit is performed for the reference channel $\psi' \to J/\psi\pi^+\pi^-$, and the resolution parameters are then fixed for the fit of the X(3872). The mass, determined by the fit, is $(3871.84 \pm 0.27 \pm 0.19)$ MeV. Including the new Belle result, the updated world-average mass of the X(3872) is $m_X = (3871.67 \pm 0.17)$ MeV. If the X(3872) is an S-wave $D^{*0}\overline{D}^0$ molecular state, the binding energy E_b would be given by the mass difference $m(X) - m(D^{*0}) - m(D^0)$. With the current value of $m(D^0) + m(D^{*0}) = (3871.79 \pm 0.30)$ MeV [9], a binding energy of $E_b = (-0.12 \pm 0.35)$ MeV can be calculated, which is surprisingly small and would indicate a very large radius of the molecular state.

The best upper limit for the $X(3872)$ width was 2.3 MeV (with 90% C.L.), obtained by previous Belle measurement [10]. The 3-dimensional fits are more sensitive to the natural width, which is smaller than the detector resolution ($\sigma \sim 4$ MeV). Due to the fit sensitivity and the calibration performed on the reference channel $\psi' \to J/\psi\pi^+\pi^-$, the updated upper limit for the $X(3872)$ width is about $1/2$ of the previous value: $\Gamma(X(3872)) < 1.2$ MeV at 90% C.L.

Previous studies performed by several experiments suggested two possible J^{PC} assignments for the $X(3872)$, 1^{++} and 2^{-+}. In the recent Belle analysis [20], the $X(3872)$ quantum numbers were also studied with the full available data sample collected at the $\Upsilon(4S)$ resonance. At the current level of statistical sensitivity it is not possible to distinguish completely between the two possible quantum number assignments, so both hypotheses are still allowed. Possible C-odd neutral partners of X(3872) are also searched, but no signal is found for this type of states.

4 Summary and Conclusions

Many new particles have already been discovered during the operation of the Belle experiment at the KEKB collider, and some of them are mentioned in this report. Some recent Belle results also indicate that analogs to exotic charmonium-like states can be found in $b\overline{b}$ systems. Although the operation of the experiment has finished, data analyses are still ongoing and therefore more interesting results on charmonium(-like) and bottomonium(-like) spectroscopy can still be expected from Belle in the near future.

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