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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, while at the end of its operation it was running mainly at the $\Upsilon(5S)$ resonance. 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 Charmonium and Charmonium-like States

2.1 η_c and $\eta_c(2S)$ in B meson decays

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 $h_c(1P)$ [3,4] with J^{PC}=0^{-+} and 1^{+-}, respectively.

Still, many questions about the lightest charmonium states have been unanswered. For example, the width of the $\eta_c(1S)$ has been determined with large discrepancies between experiments with different production mechanisms: in J/ψ and $\psi(2S)$ radiative decays $\Gamma_{\eta_c} \simeq 15$ MeV, while in B meson decays or $\gamma\gamma \to \eta_c$ processes, $\Gamma_{\eta_c} \simeq 30$ MeV [5]. In a recent Belle analysis [6] a data sample of 535 million of $B\overline{B}$ pairs is used for the study of $B^+ \to K^+\eta_c(\to K_S K^\pm \pi^\mp)$ decays[1]. The mass and the width of the η_c were determined by a 2-dimensional fit of the invariant mass

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[1] In this review, the inclusion of charge-conjugated states is always implied.

Γ_{η_c} [MeV]	Production Mechanism	Measured by
$35.1\pm3.1^{+1.0}_{-1.6}$	B decays	Belle [6]
$30.5\pm1.0\pm0.9$	$\psi'\to\gamma\eta_c$	BESIII [7]
$28.1\pm3.2\pm2.2$	$\gamma\gamma\to\eta_c$	Belle [8]
$31.7\pm1.2\pm0.8$	$\gamma\gamma\to\eta_c$	BABAR [9]
$36.3^{+3.7}_{-3.6}\pm4.4$	B decays	BABAR [10]

Table 1. Recent measurements of the η_c width.

$M_{inv}(K_S K\pi)$ vs. the angle between K_S and K^+ from B^+ in the η_c centre-of-mass system. Since η_c is a pseudoscalar meson, the angular distribution should be flat, but significant P- and D-wave components from non-resonant charmless B background decays are also observed. By including the above angle into the fit, the interference with the background seems to be correctly taken into account, and as a result the measured η_c width, listed in Table 1, is found to be consistent with other recent measurement. The η_c mass is determined to be $(2985.4\pm1.5^{+0.2}_{-2.0})$ MeV.

The same study [6] is performed also for the $\eta_c(2S)$ meson. For this first radially excited 0^{-+} $c\overline{c}$ state the width measurement is important, because the potential model predictions are less reliable due to the vicinity of the $D^0\overline{D}^0$ threshold. The analysis shows, that here the interference with the non-resonant background is even larger as in the case of the η_c. The measured width is $\Gamma_{\eta_c(2S)}=$ $(6.6^{+8.4+2.6}_{-5.1-0.9})$ MeV for the fit with interference and $(41.1\pm12.0^{+6.4}_{-10.9})$ MeV, when the interference is not taken into account, *i.e.* for the fit of the invariant mass only. The factor 5 smaller width of the $\eta_c(2S)$ when compared to the η_c can be explained only by the wave function differences, since both states decay hadronically via two gluons. With the new measurement, the error on the world average of the $\eta_c(2S)$ width is decreased for almost a factor of 2.

2.2 The X(3872) news

The story about new charmonium-like states (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 [11]. The new state, called X(3872), was soon confirmed and also intensively studied by the CDF, DØ and *BABAR* collaborations [12–20]. 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 [5]. 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 [21]. Pure $D^0\overline{D}^{*0}$

Experiment [Reference]	Measured X(3872) mass [MeV]
CDF [24]	3871.61±0.16±0.19
BaBar (B^+) [25]	3871.4±0.6±0.1
BaBar (B^0) [25]	3868.7±1.5±0.4
DØ [12]	3871.8±3.1±3.0
Belle [23]	3871.84±0.27±0.19
LHCb [26]	3871.96±0.46±0.10
Updated World Average	3871.67±0.17

Table 2. Measurements of the X(3872) mass. First error is due to limited statistics, while the second corresponds to systematic uncertainties.

molecular model [22] 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 [20] 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 Υ(4S) resonance [23]. 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 $M_{bc}= \sqrt{(E^{cms}_{beam})^2 - (p^{cms}_B)^2}$ (with the beam energy E^{cms}_{beam} and the B-meson momentum p^{cms}_B both measured in the centre-of-mass system), the invariant mass $M_{inv}(J/\psi\pi^+\pi^-)$ and the energy difference $\Delta E=E^{cms}_B - E^{cms}_{beam}$ (where E^{cms}_B 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 listed in Table 2 in comparison to other precise measurements. Including the new Belle result, the updated world-average mass of the X(3872) is m_X=(3871.67±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 ± 0.30) MeV [5], a binding energy of E_b=(−0.12±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 [11]. The 3-dimensional fits are more sensitive to the natural width, which is smaller than the detector resolution (σ ~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 [21], the $X(3872)$ quantum numbers were also studied with the full available data sample collected at the $\Upsilon(4S)$ resonance. Although at the current level of statistical sensitivity it is not possible to distinguish completely between the two possible quantum number assignments, the study shows that quantum numbers $J^{PC}=1^{++}$ seem to be slightly preferable for the $X(3872)$ state.

3 Bottomonium and Bottomonium-like States

An interesting question is whether in the $b\overline{b}$ systems there exist analogous "XYZ" states, predicted by many of the models proposed to explain the charmonium-like exotic states. Also, even for regular bottomonium states there are a lot of unanswered questions. Some of the answers are expected to be given by analyses of the Belle data sample of 121 fb^{-1}, collected at the energy of the $\Upsilon(5S)$ resonance.

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 [33]. If these transitions are only from the $\Upsilon(5S)$ resonance, then the corresponding partial widths are between 0.5 and 0.9 MeV. These values are more than two orders of magnitude larger than the corresponding partial widths for $\Upsilon(4S)$, $\Upsilon(3S)$ and $\Upsilon(2S)$ decays to $\pi^+\pi^-\Upsilon(1S)$. Recent CLEO-c results for the process $e^+e^- \to h_c(1P)\pi^+\pi^-$ showed that its rate is comparable to the process $e^+e^- \to J/\psi\pi^+\pi^-$ at $\sqrt{s} = 4170$ MeV and found an indication of even higher transition rate at the $Y(4260)$ energy [34]. Analogously, these results imply that the $h_b(mP)$ production might be enhanced in the region of the Y_b and motivate a search for the $h_b(mP)$ 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 [35]. 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.

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 [36]. 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: $M(Z_b(10610)) = (10608.4 \pm 2.0)$ MeV, $\Gamma(Z_b(10610)) = (15.6 \pm 2.5)$ MeV and $M(Z_b(10650)) = (10653.2 \pm 1.5)$ MeV, $\Gamma(Z_b(10650)) = (14.4 \pm 3.2)$ 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), which could indicate a molecular nature of the two observed states. Angular analysis of charged pion distributions favors the $J^P = 1^+$ spin-parity assignment for both $Z_b(10610)$ and $Z_b(10650)$.

4 Summary and Conclusions

The Belle experiment at the KEKB collider provides an excellent environment for charm and charmonium spectroscopy. As a result, many new particles have already been discovered during the Belle operation, 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. As the operation of the experiment has just finished in June 2010, more interesting results on charmonium(-like) and bottomonium(-like) spectroscopy can still be expected from Belle in the near future.

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