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Recent Spectroscopy Results from Belle

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Abstract. In this paper we present selected spectroscopy results based on measurements performed with the experimental data collected by the Belle detector, which has been operating at the KEKB asymmetric-energy e^+e^- collider in the KEK laboratory in Tsukuba, Japan. The selection of results is based on the interest, expressed at the workshop.

1 Introduction

The Belle detector [1] at the asymmetric-energy e^+e^- collider KEKB [2] was in operation between 1999 and 2010, and during this time it has accumulated about 1 ab^{-1} of data. The KEKB collider, often called a *B Factory*, was mostly operating around the $\Upsilon(4S)$ resonance, and as a result the Belle experiment was able to collect an impressive sample of about 772 million pairs of $B\overline{B}$ mesons. However, the experiment has also accumulated substantial data samples at other Υ resonances, like $\Upsilon(1S)$, $\Upsilon(2S)$ $\Upsilon(5S)$ and $\Upsilon(6S)$, as well as in the nearby continuum. In particular, the data samples collected at both, the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances, are the largest available in the world, corresponding to integrated luminosities of 800 fb^{-1} and 123 fb^{-1}, respectively [3]. Large amount of collected experimental data and excellent detector performance enabled many interesting spectroscopic results, including discoveries of new charmonium(-like) and bottomonium(-like) hadronic states and studies of their properties. This report focuses on some of the results, which were discussed at the workshop.

2 Charmonium and Charmonium-like States

At the start of the operation of the B Factories [4] the charmonium spectroscopy was a well established field: the experimental spectrum of $c\overline{c}$ states below the $D\overline{D}$ threshold were in good agreement with the theoretical prediction (see e.g. [5]), with the last remaining $c\overline{c}$ states below the open-charm threshold soon to be discovered [6], and no states outside of the conventional charmonium picture. However, the situation was drastically changed with the discoveries of new charmonium-like states (so called "XYZ" states).

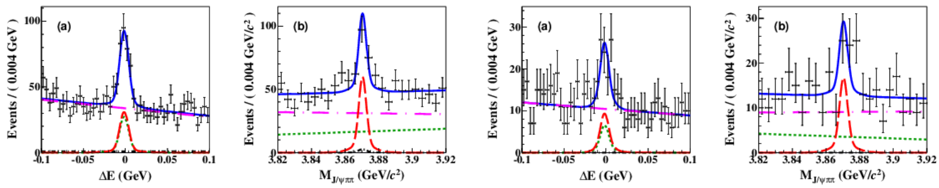

Fig. 1. Projections of the (ΔE, $M_{J/\psi\pi\pi}$) fit for the $B^0 \to X(3872)K^+\pi^-$ decay mode ((a),(b) left) and the $B^\pm \to X(3872)K^0_S\pi^\pm$ decay mode ((a),(b) right), with $X(3872) \to J/\psi\pi^+\pi^-$. The curves show the signal (red long-dashed curve), the background components (black dash-dotted line for the component peaking in $M_{J/\psi\pi\pi}$ but nonpeaking in ΔE, green dashed line for the one peaking in ΔE but nonpeaking in $M_{J/\psi\pi\pi}$, and magenta long dash-dotted line for combinatorial background), and the overall fit (blue solid curve).

2.1 The $X(3872)$-related news

The story about the "XYZ" states began in 2003, when Belle collaboration reported on $B^+ \to K^+J/\psi\pi^+\pi^-$ analysis, where a new state decaying to $J/\psi\pi^+\pi^-$ was discovered [7]. The new state, called $X(3872)$, was soon confirmed by the CDF, DØ, *BABAR* collaborations [8], and recently also by the LHC experiments [9]. The properties of this narrow state ($\Gamma = (3.0^{+1.9}_{-1.4} \pm 0.9)$ MeV) with a mass of (3872.2 ± 0.8) MeV, which is very close to the $D^0\overline{D}^{*0}$ threshold [10], have been intensively studied by Belle and other experiments [11]. These studies determined the $J^{PC} = 1^{++}$ assignment, and suggested that the $X(3872)$ state is a mixture of the conventional 2^3P_1 $c\bar{c}$ state and a loosely bound $D^0\overline{D}^{*0}$ molecular state.

In spite of the theoretical and experimental progress in understanding of the $X(3872)$, studies of several $X(3872)$ production modes, as well as search for new decay modes are still needed to fully understand the internal structure of this state. Recently, the Belle collaboration has presented the results of searches for $X(3872)$ production via the $B^0 \to X(3872)K^+\pi^-$ and $B^+ \to X(3872)K^0_S\pi^+$ decay modes, where the $X(3872)$ decays to $J/\psi\pi^+\pi^-$ on a data sample containing 772×10^6 $B\bar{B}$ events [12]. The same selection criteria as for the $B \to X(3872)K\pi$ signal events was also used to isolate the sample of $B \to \psi(2S)K\pi$ events for the calibration. The analysis (see Fig. 1 for results of the (ΔE, $M_{J/\psi\pi\pi}$) fit) yielded the first observation of the $X(3872)$ in the decay $B^0 \to X(3872)K^+\pi^-$, with the measured branching ratio of $\mathcal{B}(B^0 \to X(3872)(K^+\pi^-)) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (7.9 \pm 1.3(\text{stat}) \pm 0.4(\text{syst})) \times 10^{-6}$. The result for the $\mathcal{B}(B^+ \to X(3872)K^0\pi^+) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (10.6 \pm 3.0(\text{stat}) \pm 0.9(\text{syst})) \times 10^{-6}$ shows that $B^0 \to X(3872)K^*(892)^0$ does not dominate the $B^0 \to X(3872)(K^+\pi^-)$ decay, which is in clear contrast to the $\psi(2S)$ case. No evident peaks were found in distributions of the $X(3872)\pi$ and $X(3872)K$ invariant masses.

If $X(3872)$ is indeed a $D^0\bar{D}^{*0}$ molecule, other "X(3872)-like" molecular states with different quantum numbers can exist. Some may be revealed in the decays to final states containing the η_c meson. For example, a $D^0\bar{D}^{*0} - \bar{D}^0D^{*0}$ combination (denoted by $X_1(3872)$) with quantum numbers $J^{PC} = 1^{+-}$ would have a mass around 3.872 GeV/c^2 and would decay to $\eta_c\rho$ and $\eta_c\omega$. Combina-

Table 1. Results of branching fraction measurements for the B decays containing an intermediate exotic resonance. For $Z(3900)^0$ and $Z(4020)^0$ resonances the assumed masses are close to those of their charged partners.

Resonance	Decay mode	Upper limit (90% C.L.)
$X_1(3872)$	$\eta_c\pi^+\pi^-$	3.0×10^{-5}
	$\eta_c\omega$	6.9×10^{-5}
$X(3730)$	$\eta_c\eta$	4.6×10^{-5}
	$\eta_c\pi^0$	5.7×10^{-6}
$X(4014)$	$\eta_c\eta$	3.9×10^{-5}
	$\eta_c\pi^0$	1.2×10^{-5}
$Z(3900)^0$	$\eta_c\pi^+\pi^-$	4.7×10^{-5}
$Z(4020)^0$		1.6×10^{-5}
$X(3915)$	$\eta_c\eta$	3.3×10^{-5}
	$\eta_c\pi^0$	1.8×10^{-5}

tions of $D^0\bar{D}^0 + \bar{D}^0D^0$, denoted by $X(3730)$, and $D^{*0}\bar{D}^{*0} + \bar{D}^{*0}D^{*0}$, denoted by $X(4014)$, with quantum numbers $J^{PC} = 0^{++}$ would decay to $\eta_c\eta$ and $\eta_c\pi^0$. The mass of the $X(3730)$ state would be around $2m_{D^0} = 3.730$ GeV/c^2 while that of the $X(4014)$ state would be near $2m_{D^{*0}} = 4.014$ GeV/c^2. These molecular-state candidates were searched for in the recent Belle analysis [13]. In addition, neutral partners of the $Z(3900)^\pm$ [14] and $Z(4020)^\pm$ [15], and a poorly understood state $X(3915)$ were also searched for. The analysis was performed on the complete Belle data sample, searching for B decays to selected final states with the η_c meson. The η_c mesons were reconstructed via the $K^0_S K^\pm\pi^\mp$ mode and then four decays of charged B mesons were studied: 1.) $B^\pm \to K^\pm X \to K^\pm(\eta_c\pi^+\pi^-)$, where $X_1(3872)$, $Z(3900)^0$ and $Z(4020)^0$ were looked for; 2.) $B^\pm \to K^\pm X \to K^\pm(\eta_c\omega)$, where $X_1(3872)$ was looked for; 3.) $B^\pm \to K^\pm X \to K^\pm(\eta_c\eta)$, where $X(3730)$, $X(4014)$ and $X(3915)$ were looked for; 4.) $B^\pm \to K^\pm X \to K^\pm(\eta_c\pi^0)$, where $X(3730)$, $X(4014)$ and $X(3915)$ were looked for. No signal was observed and therefore only 90% confidence level upper limits were set on the product of branching fractions to the above mentioned intermediate states and decay branching fractions of these states in the range $(0.6 - 6.9) \times 10^{-5}$ (see table 1). Since the obtained upper limits for these exotic states are based on the full Belle data sample and are roughly of the same order as analogous quantities for their presumed partners (compare $\mathcal{B}(B^\pm \to K^\pm X_1(3872)) \times \mathcal{B}(X_1(3872) \to \eta_c\pi^+\pi^-)$ and $\mathcal{B}(B^\pm \to K^\pm X(3872)) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$ from ref. [11]), more information about the nature of these states could only be extracted from the larger data sample, collected for example by the Belle II experiment [16].

2.2 Charged $c\bar{c}$-like states

In 2008 an exciting discovery of a new charmonium-like state was reported [17] by Belle in the $B^{+,0} \to K^{0,-}\pi^+\psi(2S)$ analysis[1], where a strong enhancement was

[1] Throughout the document, charge-conjugated modes are included in all decays, unless explicitly stated otherwise.

obtained in the $\pi^+\psi(2S)$ invariant mass distribution. The observed charged resonance, named $Z^+(4430)$, was characterised by a product branching fraction of $\mathcal{B}(\overline{B}^0 \to K^- Z^+(4430)) \times \mathcal{B}(Z^+(4430) \to \pi^+\psi(2S)) = (4.1 \pm 1.0 \pm 1.4) \cdot 10^{-5}$, which is typical for a charmonium state. The $Z^+(4430)$ is thus seen as the first charmonium-like charged meson with a minimal quark content of $c\overline{c}u\overline{d}$ – a serious tetraquark candidate. The signature of this exotic state was also searched for by the *BABAR* collaboration [18]. The performed analysis of the $B^{-,0} \to \psi\pi^- K^{0,+}$ (ψ = J/ψ or $\psi(2S)$) decays focused on a detailed study of the $K\pi^-$ system, and used the final *BABAR* data sample of 413 fb^{-1}, but found no significant evidence for this new state.

Soon afterwards, the Belle collaboration reported the update of the previous analysis [17], reanalysing the same data set as used previously, but performing a full Dalitz plot analysis, in order to check for the possible $\psi(2S)\pi^-$ mass reflections from the $K\pi$ system [19]. Results confirmed the existence of $Z^+(4430)$ and their experimental properties. Later on, another update of this measurement was reported by Belle, performing the full four-dimensional amplitude analysis on the entire Belle data sample [20]. The parameters of the $Z^+(4430)$ were further confirmed, and at the same time the measurement constrained $Z^+(4430)$ quantum numbers to preferred $J^P = 1^+$ hypothesis.

Already the observation of the $Z^+(4430)$ state suggested that studies of $B \to K\pi(c\overline{c})$ decays could reveal other similar neutral and charged partners. Belle thus reported also on a Dalitz plot analysis of $\overline{B}^0 \to K^-\pi^+\chi_{c1}$ decays with $657 \cdot 10^6$ $B\overline{B}$ pairs. [21] The fit model for $K\pi$ resonances is the same as in the $Z^+(4430)$ Dalitz analysis, but here it includes also the $K_3^*(1780)$ meson, and the fit results suggested that a broad doubly peaked structure in the $\pi^+\chi_{c1}$ invariant mass distribution should be interpreted by two new states, called $Z^+(4050)$ and $Z^+(4250)$.

More intereseting results on charged charmonium-like states followed initial discoveries. As already mentioned above, a few years ago the BESIII and Belle collaborations reported the observation of another charged charmonium-like state, $Z^+(3900)$, which decays into $J/\psi\pi^+$ [14]. Both experiments observed the new charged state in the production process $e^+e^- \to Y(4260)$, with $Y(4260)$ decaying into the $J/\psi\pi^+\pi^-$ final state. One of the most important experimental meassages came last year from the LHCb collaboration, which reported the observation of $Z^+(4430)$ [22] in B decays. The measured parameters including the spin-parity were found to be in good agreement with the results obtained in the updated Belle analysis on $Z^+(4430)$. So finally, after several years, the existence of a new type of hadrons, charged charmonium-like states with their quark content being different from mesonic or baryonic, is confirmed.

The Belle collaboration continues the research, consistent with the rich tradition in this field: Last year the Belle reported on a new measurement with a full four-dimensional amplitude analysis of the 3-body decay $B \to J/\psi\pi^+K$ [23], where another charged charmonium-like state was observed. The state, called $Z^+(4200)$, with a preferred spin-parity 1^+ was observed in the $J/\psi\pi^+$ decay mode. Within this analysis, the first evidence for the decay $Z^+(4430) \to J/\psi\pi^+$ was found, which is the second decay mode of the $Z^+(4430)$ state. Fig. 2 shows the

$M^2(J/\psi\pi^+)$ projections of the Dalitz plot. The curves indicate the fit results with and without the new $Z(4200)+$ state.

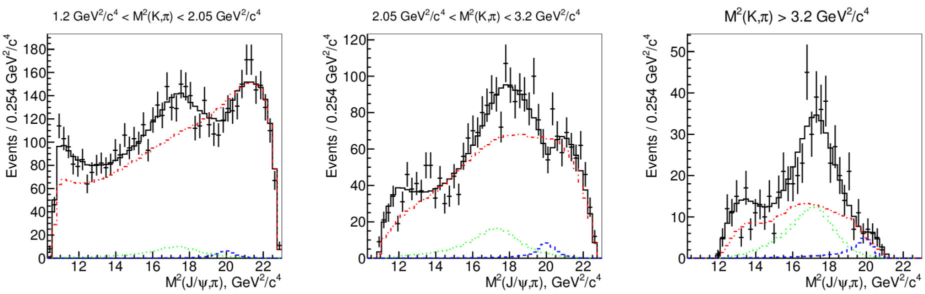

Fig. 2. The fit results with the $Z^+(4200)$ ($J^P = 1^+$) in the default model. The points with error bars are data; the solid histograms are fit results, the dashed histograms are the $Z^+(4430)$ contributions, the dotted histograms are the $Z^+(4200)$ contributions and the dash-dotted histograms are contributions of all K^* resonances.

3 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. 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. These results are eagerly awaited by the community and will be widely discussed at various occassions, in particular at workshops and conferences.

Even more progress in the spectroscopy field is expected from the huge available data sample, which will come from the Belle II experiment [16].

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Popolni eksperimenti pri fotoprodukciji psevdoskalarnih mezonov

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Predstavim problem, kako enolično izvrednotiti amplitude za fotoprodukcijo iz tako imenovanih popolnih eksperimentov. Pri tem smo lahko pozorni na določanje amplitude za celotno tvorbo ali pa na določanje multipolov. Na kratko obravnavam oba primera. Podrobneje opišem preliminarne rezultate prilagajanja multipolov kakor tudi določanja njihovih napak pri nedavnih meritvah polarizacije v področju resonance Δ.

Novi spektroskopski rezultati iz laboratorija Belle

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V prispevku predstavimo izbrane rezultate spektroskopskih meritev, opravljenih na izmerjenih podatkih, pridobljenih z detektorjem Belle, ki je stal ob trkalniku KEKB v laboratoriju KEK v Cukubi, na Japonskem. Trkalnik je obratoval med letoma 1999 in 2010, v tem času pa je s stabilnim delovanjem pri trkih elektronov in pozitronov različnih energij postal prava "tovarna" parov mezonov B, mezonov D in še leptonov tau. Ogromne količine kakovostnih podatkov so omogočile tudi številne spektroskopske meritve. Izbor tukaj predstavljenih rezultatov ustreza zanimanju in razpravam na delavnici.

Produkcija mezonov eta in kaonov v kiralnem kvarkovem modelu

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Formalizem sklopljenih kanalov, ki vključuje kvazi vezana večkvarkovska stanja, uporabimo za izračun sipalnih in fotoprodukcijskih amplitud mezonov eta in kaonov. Sklopitvene konstante in oblikovne faktorje določimo v modelu oblačne vreče. Model napove znatne amplitude v parcialnih valovih P13, P33 in S11, v skladu z najnovejšimi analizami parcialnih valov skupine iz Mainza in skupine iz Bonna in Peterburga.