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Selected Recent Results from Belle on Hadron Spectroscopy

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Abstract. The paper reviews selected recent spectroscopy results of measurements performed with the experimental data sample collected by the Belle detector, which has been operating between 1999 and 2010 at the KEKB asymmetric-energy e^+e^- collider in the KEK laboratory in Tsukuba, Japan. The sample of collected experimental data enables various interesting measurements, including ones in hadron spectroscopy. Due to size of the data sample and complexity of experimental procedures, measurements are still being performed and new results published even now, several years after the end of the Belle detector operation. The selection of recent results presented here corresponds to the scope of the workshop and reflects interests of its participants.

1 Introduction

The Belle detector [1] at the asymmetric-energy e^+e^- collider KEKB [2] has during its operation, between 1999 and 2010, accumulated an impressive sample of data, corresponding to about 1 ab^{-1} of integrated luminosity. The KEKB collider, often called a *B Factory*, was operating mostly around the $\Upsilon(4S)$ resonance, but also at other Υ resonances, like $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(5S)$ and $\Upsilon(6S)$, as well as in the nearby continuum [3]. As a result of both successful accelerator operation and an excellent detector performance, the large amount of collected experimental data enabled many valuable measurements in the field of hadron spectroscopy, including discoveries of new charmonium(-like) and bottomonium(-like) hadronic states together with studies of their properties. This paper reports on some of the recent results, selected according to the scope of the workshop.

2 Charmonium and Charmonium-like States

The charmonium spectroscopy was a well established field around the year 2000, when the two B Factories started their operation [4]. At that time the experimental spectrum of $c\bar{c}$ states below the $D\overline{D}$ threshold was in good agreement with the theoretical prediction (see e.g. ref. [5]), and with the last remaining $c\bar{c}$ states below the open-charm threshold soon to be discovered [6]. However, instead of a peaceful era, the true renaissance in the field actually started with the discoveries of the so called "XYZ" states—new charmonium-like states outside of the conventional charmonium picture.

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}

2.1 The $X(3872)$-related news

The "XYZ" story begins in 2003, when Belle collaboration reported on $B^+ \to K^+ J/\psi\pi^+\pi^-$ analysis[1], where a new state decaying to $J/\psi\pi^+\pi^-$ was discovered [7]. The new state, called $X(3872)$, was confirmed by the CDF, DØ, *BABAR* collaborations [8], and later 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 order to fully understand the nature and internal structure of the $X(3872)$, further studies of $X(3872)$ production and decay modes are needed. One example of such studies is the search 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 $J/\psi\pi^+\pi^-$, which was presented by the Belle collaboration last year [12]. The analysis was performed on a data sample containing 772×10^6 $B\bar{B}$ events, yielding the first observation of the $X(3872)$ in the decay $B^0 \to X(3872)K^+\pi^-$, with the measured branching fraction 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 charmonium behaviour in the $B \to \psi(2S)K\pi$ case.

The $D^0\bar{D}^{*0}$ molecular hypothesis of $X(3872)$ allows for the existence of other "$X(3872)$-like" molecular states with different quantum numbers. Some of these states could be revealed in studies of 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

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

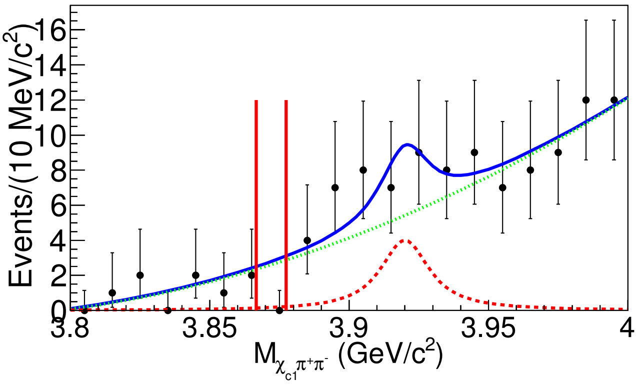

Fig. 1. The $\chi_{c1}\pi^+\pi^-$ invariant mass spectrum for $B^+ \to \chi_{c1}\pi^+\pi^-K^+$ candidates. Two vertical red lines show the $\pm 3\sigma$ window to search for $X(3872) \to \chi_{c1}\pi^+\pi^-$. The curves show the $\chi_{c1}(2P)$ signal (red dashed) and the background (green dotted) and the overall fit (blue solid).

would decay to $\eta_c\rho$ and $\eta_c\omega$. Combinations 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, performed on the complete Belle data sample [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. All performed studies of B decays to selected final states with the η_c meson resulted in no signal being observed, thus only 90% confidence level upper limits were set on the product of branching fractions to various intermediate states and their decay branching fractions in the range $(0.6 - 6.9) \times 10^{-5}$ (see Table 1). The obtained upper limits for these exotic states are already based on the full Belle data sample and are roughly of the same order as obtained for their presumed partners (compare results from ref. [11]), so more information about the nature of these states could only be extracted from the larger data sample, which will be available at the Belle II experiment [16].

Recently Belle collaboration has studied the multi-body B decay modes with χ_{c1} and χ_{c2} in the final state, using the full Belle data sample of 772×10^6 $B\overline{B}$ events [17]. This study is important to understand the detailed dynamics of B meson decays, but at the same time these decays could be exploited to search for charmonium and charmonium-like exotic states in one of the intermediate final states such as $\chi_{cJ}\pi$ and $\chi_{cJ}\pi\pi$. For example, looking at the $\chi_{c1}\pi^+\pi^-$ invariant mass spectrum in $B \to \chi_{c1}\pi^+\pi^-K$ decays, one can search for $X(3872)$ and/or $\chi_{c1}(2P)$, which could be the conventional charmonium component of the $X(3872)$ state. The $\chi_{c1}(2P)$ component may have a substantial decay rate to $\chi_{c1}\pi^+\pi^-$ because of no obvious conflict in quantum numbers and observations of di-pion transitions between χ_{bJ} states in the bottomonium system. In case that X(3872) is not a mixed state and hence $\chi_{c1}(2P)$ is a physically observable state, its decay to $\chi_{c1}\pi^+\pi^-$ would still be expected. Its mass is predicted to be about 3920 MeV/c^2, assuming that it lies between $\chi_{c2}(2P)$ and the X(3915) that is interpreted as $\chi_{c0}(2P)$ by PDG [10]. The measurement yields $\mathcal{B}(B \to \chi_{c1}X)$= $(3.03 \pm 0.05(\text{stat}) \pm 0.24(\text{syst})) \times 10^{-3}$ and $\mathcal{B}(B \to \chi_{c2}X)$= $(0.70 \pm 0.06(\text{stat}) \pm 0.10(\text{syst})) \times 10^{-3}$. For the first time, χ_{c2} production in exclusive B decays in the modes $B^0 \to \chi_{c2}\pi^-K^+$ and $B^+ \to \chi_{c2}\pi^+\pi^-K^+$ has been observed, along with first evidence for the $B^+ \to \chi_{c2}\pi^+K^0_S$ decay mode. For χ_{c1} production, the first observation in the $B^+ \to \chi_{c1}\pi^+\pi^-K^+$, $B^0 \to \chi_{c1}\pi^+\pi^-K^0_S$ and $B^0 \to \chi_{c1}\pi^0\pi^-K^+$ decay modes is reported. For the above decay modes, a difference in the production mechanism of χ_{c2} in comparison to χ_{c1} in B decays is clearly observed. In the search for $X(3872) \to \chi_{c1}\pi^+\pi^-$ and $\chi_{c1}(2P)$, an U.L. on the product of branching fractions $\mathcal{B}(B^+ \to X(3872)K^+) \times (X(3872) \to \chi_{c1}\pi^+\pi^-)$ $[\mathcal{B}(B^+ \to \chi_{c1}(2P)K^+) \times (\chi_{c1}(2P) \to \chi_{c1}\pi^+\pi^-)] < 1.5 \times 10^{-6}$ $[1.1 \times 10^{-5}]$ is determined at the 90% C.L. (the fit to the $\chi_{c1}\pi^+\pi^-$ invariant mass distribution is shown in Figure 1) The negative result for these searches is compatible with the interpretation of X(3872) as an admixture state of a $D^0\bar{D}^{*0}$ molecule and a $\chi_{c1}(2P)$ charmonium state.

2.2 Study of $J^{PC} = 1^{--}$ states using ISR

Initial-state radiation (ISR) has proven to be a powerful tool to search for $J^{PC} = 1^{--}$ states at B-factories, since it allows one to scan a broad energy range of $\sqrt{s}$ below the initial e^+e^- centre-of-mass (CM) energy, while the high luminosity compensates for the suppression due to the hard-photon emission. Three charmonium-like 1^{--} states were discovered at B factories via initial-state radiation in the last decade: the Y(4260) in $e^+e^- \to J/\psi\pi^+\pi^-$ [18,19], and the Y(4360) and Y(4660) in $e^+e^- \to \psi(2S)\pi^+\pi^-$ [20,21]. Together with the conventional charmonium states $\psi(4040)$, $\psi(4160)$, and $\psi(4415)$, there are altogether six vector states; only five of these states are predicted in the mass region above the DD threshold by the potential models [22]. It is thus very likely, that some of these states are not charmonia, but have exotic nature—they could be multiquark states, meson molecules, quark-gluon hybrids, or some other structures. In order to understand the structure and behaviour of these states, it is therefore necessary to study them in many decay channels and with largest possible data samples available.

Recent paper from Belle collaboration reports on the experimental study of the process $e^+e^- \to \gamma\chi_{cJ}$ (J=1, 2) via initial-state radiation using the data sample of 980 fb^{-1}, collected at and around the $\Upsilon(nS)$ (n=1, 2, 3, 4, 5) resonances. For the CM energy between 3.80 and 5.56 GeV, no significant $e^+e^- \to \gamma\chi_{c1}$ and $\gamma\chi_{c2}$ signals were observed except from $\psi(2S)$ decays, therefore only upper limits on the cross sections were determined at the 90% credibility level. Reported upper limits in this CM-energy interval range from few pb to a few tens of pb. Upper limits on the decay rate of the vector charmonium [$\psi(4040)$, $\psi(4160)$, and $\psi(4415)$] and charmonium-like [Y(4260), Y(4360), and Y(4660)] states to $\gamma\chi_{cJ}$ were also reported in this study (see Table 2). The obtained results could help in better understanding the nature and properties of studied vector states.

Table 2. Upper limits on $\Gamma_{ee} \times \mathcal{B}(R \to \gamma\chi_{cJ})$ at the 90% C.L.

	χ_{c1} (eV)	χ_{c2} (eV)
$\Gamma_{ee}[\psi(4040)] \times \mathcal{B}[\psi(4040) \to \gamma\chi_{cJ}]$	2.9	4.6
$\Gamma_{ee}[\psi(4160)] \times \mathcal{B}[\psi(4160) \to \gamma\chi_{cJ}]$	2.2	6.1
$\Gamma_{ee}[\psi(4415)] \times \mathcal{B}[\psi(4415) \to \gamma\chi_{cJ}]$	0.47	2.3
$\Gamma_{ee}[Y(4260)] \times \mathcal{B}[Y(4260) \to \gamma\chi_{cJ}]$	1.4	4.0
$\Gamma_{ee}[Y(4360)] \times \mathcal{B}[Y(4360) \to \gamma\chi_{cJ}]$	0.57	1.9
$\Gamma_{ee}[Y(4660)] \times \mathcal{B}[Y(4660) \to \gamma\chi_{cJ}]$	0.45	2.1

3 Results on Charmed Baryons

Recently, a lot of effort in Belle has been put into studies of charmed baryons. Many of these analyses are still ongoing, but some of the results are already available. One example of such a result is the first observation of the decay $\Lambda_c^+ \to pK^+\pi^-$ using a 980 fb^{-1} data sample [23]. This is the first doubly Cabibbo-suppressed (DCS) decay of a charmed baryon to be observed, with statistical significance of 9.4 σ (fit results for invariant-mass distributions are shown in Figure 2). The branching fraction of this decay with respect to its Cabibbo-favoured (CF) counterpart is measured to be $\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)/\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (2.35 \pm 0.27 \pm 0.21) \times 10^{-3}$, where the uncertainties are statistical and systematic, respectively.

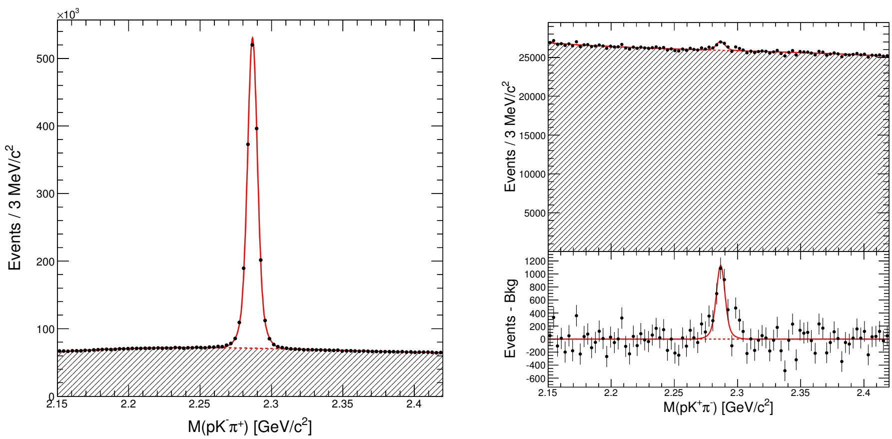

Fig. 2. Invariant mass distributions for the Λ_c^+ candidates: $M(pK^-\pi^+)$ for the CF decay mode (left) and $M(pK^+\pi^-)$ for the DCS decay mode (right, top). In the DCS case the distribution after the combinatorial-background subtraction is also shown (right, bottom). The curves indicate the fit result: the full fit model (solid) and the combinatorial background only (dashed).

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. Although the operation of the experiment finished several years ago, data analyses are still ongoing and therefore more interesting results on charmonium(-like) and bottomonium(-like) and baryon 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 occasions, in particular at workshops and conferences.

Still, the era of Belle experiment is slowly coming to an end. Further progress towards high-precision measurements—with possible experimental surprises—in the field of hadron spectroscopy are expected from the huge experimental data sample, which will be collected in the future by the Belle II experiment [16].

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