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Recent Belle Results on Hadron Spectroscopy

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Abstract. Recent results on hadron spectroscopy from the Belle experiment are reviewed in this contribution. Results are based on experimental data sample collected by the Belle detector, which was in operation between 1999 and 2010 at the KEKB asymmetric-energy e^+e^- collider in the KEK laboratory in Tsukuba, Japan. As a result of the size and quality of collected Belle experimental data, new measurements are still being performed now, almost a decade after the end of the Belle detector operation. Results from recent Belle publications on hadron spectroscopy, selected for this review, are within the scope of this workshop and reflect the interests of the participants.

1 Introduction

During its operation between 1999 and 2010, the Belle detector [1] at the asymmetric-energy e^+e^- collider KEKB [2] accumulated an impressive sample of data, corresponding to more than 1 ab^{-1} of integrated luminosity. The KEKB collider, 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]. With succesful accelerator operation and excellent detector performance, the collected experimental data sample was suitable for various measurements, including the ones in hadron spectroscopy, like discoveries of new charmonium(-like) and bottomonium(-like) hadronic states, together with studies of their properties.

2 Charmonium and Charmonium-like states

Around the year 2000, when the two B Factories started their operation [4], the charmonium spectroscopy was a well established field: the experimental spectrum of $c\bar{c}$ states below the $D\bar{D}$ threshold was in good agreement with theoretical prediction (see e.g. ref. [5]), and the last remaining $c\bar{c}$ states below the open-charm threshold were soon to be discovered [6].

2.1 The $X(3872)$-related news

However, the field experienced a true renaissance by discoveries of the so-called "XYZ" states—new charmonium-like states outside of the conventional charmonium picture. This fascinating story began 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.

If one wants to better understand the structure of X(3872), further studies of production and decay modes for this narrow exotic state are necessary. A recent example of these experimental studies at Belle 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 X(3872) decays to $J/\psi\pi^+\pi^-$ [12]. The results, obtained on a data sample containing 772×10^6 $B\bar{B}$ events, show 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.

Another consequence of the $D^0\bar{D}^{*0}$ molecular hypothesis of X(3872) is an existence of "X(3872)-like" molecular states with different quantum numbers. Searches for some of these states were performed in another recent Belle analysis [13], using final states containing the η_c meson. A state $X_1(3872)$, a $D^0\bar{D}^{*0} - \bar{D}^0D^{*0}$ combination with $J^{PC} = 1^{+-}$, and two states with $J^{PC} = 0^{++}$, X(3730) (combination of $D^0\bar{D}^0 + \bar{D}^0D^0$) and X(4014) (combination of $D^{*0}\bar{D}^{*0} + \bar{D}^{*0}D^{*0}$), were searched for. Additionally, neutral partners of the $Z(3900)^{\pm}$ [14] and $Z(4020)^{\pm}$ [15], and a poorly understood state X(3915) were also included in the search. No signal was observed in B decays to selected final states with the η_c meson for any of these exotic states, so only 90% confidence-level upper limits were set.

The interpretation of X(3872) being an admixture state of a $D^0\bar{D}^{*0}$ molecule and a $\chi_{c1}(2P)$ charmonium state was also compatible with results of the recent Belle study of 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 [16]. 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 $\chi_{cJ}\pi\pi$.

These recent results were already obtained with the complete Belle data sample, so more information about the nature of mentioned exotic states could only be extracted from the larger data sample, which will be available at the Belle II experiment [17].

2.2 Alternative $\chi_{c0}(2P)$ candidate

The charmonium-like state X(3915) was observed by the Belle Collaboration in $B \to J/\psi\omega K$ decays [18]; originally it was named Y(3940). Subsequently, it was

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

also observed by the *BABAR* Collaboration in the same B decay mode [19] and by both Belle and *BABAR* in the process $\gamma\gamma \to X(3915) \to J/\psi\omega$ [20]. The quantum numbers of the X(3915) were measured to be $J^{PC} = 0^{++}$, and as a result, the X(3915) was identified as the $\chi_{c0}(2P)$ in the 2014 PDG tables [21].

However, many properties of the X(3915) state were found to be inconsistent with this identification. For example, the $\chi_{c0}(2P) \to D\overline{D}$ decay mode is expected to be dominant, but has not yet been observed experimentally for the X(3915). Also, the measured X(3915) width of (20 ± 5) MeV is much smaller than expected $\chi_{c0}(2P)$ width of $\Gamma \gtrsim 100$ MeV [22]. A later reanalysis [23] of the data from Ref. [20] showed that both $J^{PC} = 0^{++}$ and 2^{++} assignments are possible. As a result of these considerations, the X(3915) was no longer identified as the $\chi_{c0}(2P)$ in the 2016 PDG tables [10]; and there was enough motivation for Belle Collaboration to perform an updated analysis of the process $e^+e^- \to J/\psi D\overline{D}$.

This latest analysis [24] used the 980 fb^{-1} data sample, collected at or near the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances. In addition to this 1.4 times increased statistics with respect to previous measurement, a sophisticated multivariate method was used to improve the discrimination of the signal and background events, and an amplitude analysis was performed to study the J^{PC} quantum numbers of the $D\overline{D}$ system. As a result of this analysis, a new charmonium-like state, the $X^*(3860)$, was observed in the process $e^+e^- \to J/\psi D\overline{D}$. The mass of this state is determined to be (3862^{+26+40}_{-32-13}) MeV and its width is $(201^{+154+88}_{-67\ -82})$ MeV. The $X^*(3860)$ quantum number hypotheses $J^{PC} = 0^{++}$ and 2^{++} are compared using MC simulation. Monte Carlo pseudoexperiments are generated according to the fit result with the 2^{++} $X^*(3860)$ signal in data and then fitted with the 2^{++} and 0^{++} signals (see Figure 1). The $J^{PC} = 0^{++}$ hypothesis is favoured over the 2^{++} hypothesis at the level of 2.5σ.

The new state $X^*(3860)$ seems to be a better candidate for the $\chi_{c0}(2P)$ charmonium state than the X(3915): the measured $X^*(3860)$ mass is close to potential model prediction for the $\chi_{c0}(2P)$, while the preferred quantum numbers are $J^{PC} = 0^{++}$, although the 2^{++} hypothesis is not excluded.

2.3 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 $e^+e^- \to J/\psi\pi^+\pi^-$ [25,26], and the Y(4360) and Y(4660) in $e^+e^- \to \psi(2S)\pi^+\pi^-$ [27,28]. 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 [29]. 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.

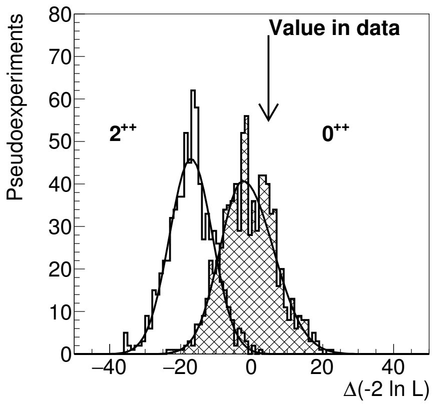

Fig. 1. Comparison of the 0^{++} and 2^{++} hypotheses in the default model (constant nonresonant amplitude). The histograms are distributions of $\Delta(-2\ln L)$ in MC pseudoexperiments generated in accordance with the fit results with 2^{++} (open histogram) and 0^{++} (hatched histogram) signals.

Recent paper from Belle collaboration [30] 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 1). The obtained results could help in better understanding the nature and properties of studied vector states.

	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

Table 1. Upper limits on $\Gamma_{ee} \times \mathcal{B}(R \to \gamma\chi_{cJ})$ at the 90% C.L.

Initial-state radiation technique was also used in the new Belle measurement of the exclusive $e^+e^- \to D^{(*)\pm}D^{*\mp}$ cross sections as a function of the center-of-mass energy from the $D^{(*)\pm}D^{*\mp}$ threshold through $\sqrt{s} = 6.0$ GeV [31]. The analysis is based on a Belle data sample collected with an integrated luminosity of 951 fb^{-1}. The accuracy of the cross section measurement is increased by a factor of two over the previous Belle study, due to the larger data set, the improved track reconstruction, and the additional modes used in the D and D^* reconstruction. The complex shape of the $e^+e^- \to D^{*+}D^{*-}$ cross sections can be explained by the fact that its components can interfere constructively or destructively. The fit of this cross section is not trivial, because it must take into account the threshold and coupled-channels effects.

Finally, the first angular analysis of the $e^+e^- \to D^{*\pm}D^{*\mp}$ process was performed within this study, allowing the decomposition of the corresponding exclusive cross section into three possible components for the longitudinally, and transversely-polarized $D^{*\pm}$ mesons, as shown in Figure 2. The obtained components have distinct behaviour near the $D^{*+}D^{*-}$ threshold. The only non-vanishing component at higher energy is the TL helicity of the $D^{*+}D^{*-}$ final state. The measured decomposition allows the future measurement of the couplings of vector charmonium states into different helicity components, useful in identifying their nature and in testing the heavy-quark symmetry.

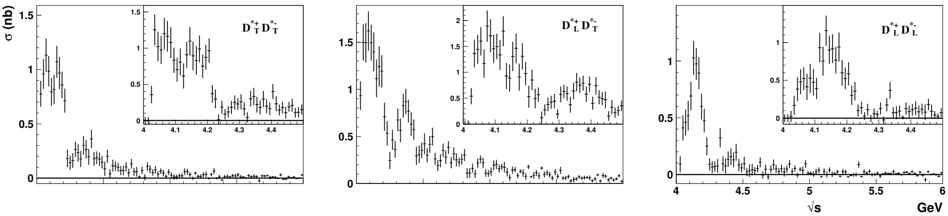

Fig. 2. The components of the $e^+e^- \to D^{*+}D^{*-}\gamma_{ISR}$ cross section corresponding to the different $D^{*\pm}$'s helicities. (The labels and units for the horizontal axis, common in all three cases, are shown only for the right plot.

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 [32]. 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 3). 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.

This year the results of the most recent baryon study were published [33]. In this study the inclusive production cross sections of hyperons and charmed

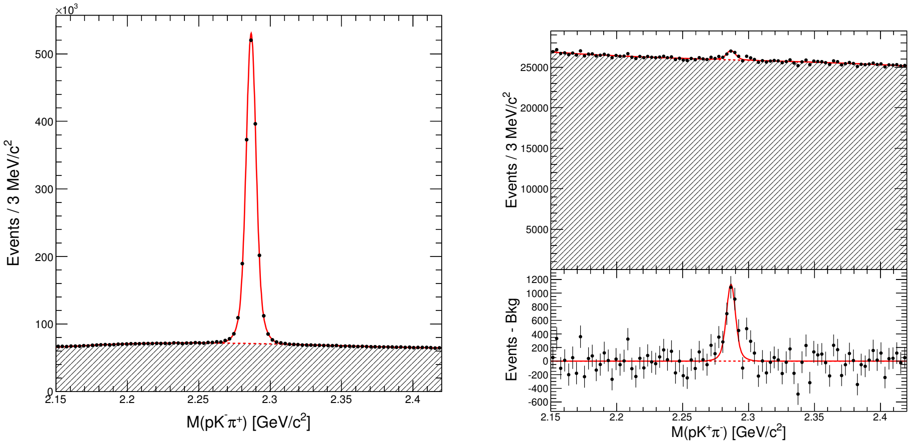

Fig. 3. Invariant mass distributions for the Λ_c^+ candidates: $M(pK^-\pi^+)$ for the CF decay mode (left) and $M(pK^+\pi^-)$ for the DCS decay mode (right, top). In the DCS case the distribution after the combinatorial-background subtraction is also shown (right, bottom). The curves indicate the fit result: the full fit model (solid) and the combinatorial background only (dashed).

baryons from e^+e^- annihilation were measured. The analysed sample corresponds to 800 fb^{-1} of Belle data collected around the $\Upsilon(4S)$ resonance. The feed-down contributions from heavy particles were estimated and subtracted, using the measured data. The direct production cross sestions of hyperons and charmed baryons were thus measured and presented for the first time (see Figure 4).

The production cross sections divided by the spin multiplicities for $S = -1$ hyperons follow an exponential function with a single slope parameter except for the $\Sigma(1385)^+$ resonance. A suppression for $\Sigma(1385)^+$ and $S = -2, -3$ hyperons is observed, which is likely a consequence of decuplet suppression and strangeness suppression in the fragmentation process. The production cross sections of charmed baryons are significantly higher than those of excited hyperons, and strong suppression of Σ_c with respect to Λ_c^+ is observed. The ratio of the production cross sections of Λ_c^+ and Σ_c is consistent with the difference of the production probabilities of spin-0 and spin-1 diquarks in the fragmentation process. This observation supports the theory that the diquark production is the main process of charmed baryon production from e^+e^- annihilation, and that the diquark structure exists in the ground state and low-lying excited states of Λ_c^+ baryons.

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 almost a decade ago,

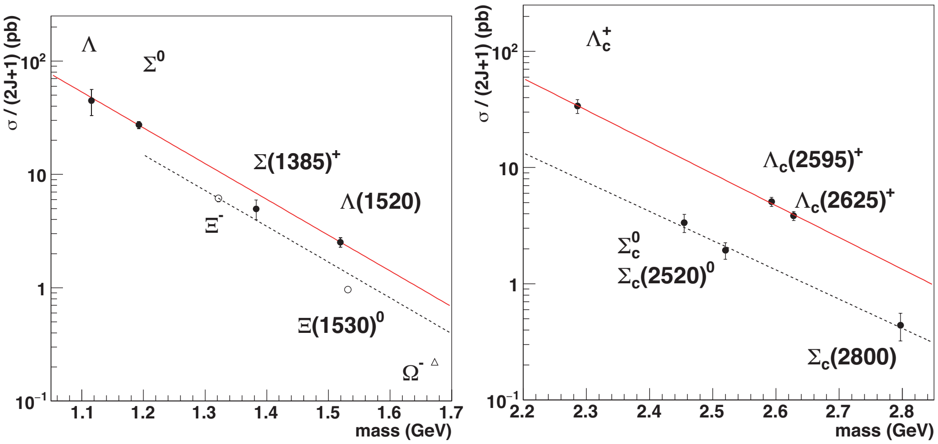

Fig. 4. Scaled direct production cross section as a function of mass of hyperons (left) and charmed baryons (right). $S = -1, -2, -3$ hyperons are shown with filled circles, open circles and a triangle, respectively.

data analyses are still ongoing and consequently more interesting results on charmonium(-like), bottomonium(-like) and baryon spectroscopy can still be expected from Belle in the near future. The 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 the 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 [17]. This future might actually start soon, since the Belle II detector begins its operation early next year.

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