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News from Belle on Hadron Spectroscopy

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Abstract. In this contribution, recent results on hadron spectroscopy from the Belle experiment are reviewed. All reported 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. Even a decade after the end of the experiment, the collected data sample is still used for new measurements. Selection of results from recent Belle publications on hadron spectroscopy is presented in this review, reflecting the scope of the workshop and interest of its participants.

1 Introduction

During a decade of succesful operation of both Belle detector[1] and KEKB accelerator[2], a large sample of experimental data was collected, corresponding to more than 1 ab^{-1} of integrated luminosity, with energies around the $\Upsilon(4S)$ resonance, but also at other Υ resonances, like $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(5S)$ and $\Upsilon(6S)$, as well as in the nearby continuum [3]. The available data has proven to offer excellent opportunities for various measurements, including the ones in hadron spectroscopy, like discoveries of new charmonium(-like) and bottomonium(-like) hadronic states, and studies of their properties.

2 Charmonium and Charmonium-like states

The field of charmonium spectroscopy attracted a lot of interest after the discovery of the state $X(3872)$, decaying to $J/\psi\pi^+\pi^-$[4], and other so-called "XYZ" states—new charmonium-like states outside of the conventional charmonium picture. Belle continues with studies in this field of research, together with other experiments.

Various experimental studies of the $X(3872)$ state determined its $J^{PC} = 1^{++}$ assignment, and suggested that this state is an admixture 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. An example of these experimental efforts is the recent study [5], where Belle performed searches for $X(3872)$ decaying to $\chi_{c1}\pi^0$. Simultaneously, a poorly understood state $X(3915)$ was also included in the search. No significant signal was found for any of the two states, since only 2.7 ± 5.5 (42 ± 14) events were observed, with a signal significance of 0.3 σ (2.3 σ) for the $B^+ \to X(3872)(\to \chi_{c1}\pi^0)K^+$ ($B^+ \to X(3915)(\to \chi_{c1}\pi^0)K^+$) decay mode. The upper limits on the product branching fractions $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to \chi_{c1}\pi^0) < 8.1 \times 10^{-6}$ and $\mathcal{B}(B^+ \to X(3915)K^+) \times \mathcal{B}(X(3915) \to \chi_{c1}\pi^0) < 3.8 \times 10^{-5}$ were determined at 90% confidence level. The null result of the search is compatible with the above mentioned interpretation of the X(3872) state, being the admixture of a conventional charmonium and a $D\bar{D}$ molecular states. Furthermore, the result for the upper limit of the ratio $\mathcal{B}(X(3872) \to \chi_{c1}\pi^0)/\mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 0.97$ at 90% confidence level, can be used to constrain the tetraquark/molecular component of the X states.

Another analysis, recently performed by Belle on the data sample corresponding to an integrated luminosity of $711\,\mathrm{fb}^{-1}$ and containing $772 \times 10^6 B\bar{B}$ pairs, focused on a search for the decay $B^0 \to X(3872)(\to J/\psi\pi^+\pi^-)\gamma$ [6]. Rare decays of B mesons are sensitive probes to study possible new physics beyond the Standard Model, which could significantly modify the branching fraction for the $B^0 \to J/\psi\gamma$ decay. Non-charmonium components of the exotic X(3872) would make the $B^0 \to X(3872)\gamma$ branching fraction smaller than that of $B^0 \to J/\psi\gamma$. The performed search resulted in finding no significant signal, so only an upper limit on the product of the branching fractions $\mathcal{B}(B^0 \to X(3872)\gamma) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$ of 5.1×10^{-7} was set at 90% confidence level.

The Y(4260) state, also known as ψ(4260) [7], is another exotic state, which draws much attention. It was first observed in the initial-state radiation (ISR) process $e^+e^- \to \gamma_{ISR}Y(4260)$ by the *BABAR* collaboration [8], and due to its production in ISR, its quantum numbers are expected to be $J^{PC} = 1^{--}$. This would make the Y(4260) a natural candidate for a conventional charmonium state with $J^{PC} = 1^{--}$, but its mass and properties are not consistent with those expected for any of the predicted conventional $c\bar{c}$ states in this mass region. Instead, the measured properties indicate the exotic nature of the Y(4260) state—it could be an admixture of charmonium and some other structures, like multiquark states or mesonic molecules, it could be a hybrid charmonium, or some other exotic object. In order to understand the structure and properties of the Y(4260) (and some other similar 1^{--} states), studies of several decay channels with large data sample are necessary.

The most recent example of such a study performed at Belle, is a search for the $B \to Y(4260)K$, $Y(4260) \to J/\psi\pi^+\pi^-$ decays using $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance [9]. The observed signal yields for these decays were $179 \pm 53^{+55}_{-41}$ events and $39 \pm 28^{+7}_{-31}$ events for the charged and neutral $B \to Y(4260)K$, $Y(4260) \to J/\psi\pi^+\pi^-$ decays, respectively, from fits to the individual decay samples; the first and second uncertainties are statistical and systematic, respectively. The signal significances are obtained to be 2.1σ and 0.9σ for the charged and neutral decays, respectively, taking into account the systematic uncertainties. The corresponding upper limits on the product of branching fractions, $\mathcal{B}(B^+ \to Y(4260)K^+) \times \mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-) < 1.4 \times 10^{-5}$ and $\mathcal{B}(B^0 \to Y(4260)K^0) \times \mathcal{B}(Y(4260) \to J/\psi\pi^+\pi^-) < 1.7 \times 10^{-5}$ determined at the 90% confidence level, are the most stringent to date. However, as these results were already based on the complete Belle data sample, more information about the nature of the $Y(4260)$ state can only be obtained by improved measurements with a larger data sample, which will only be available at the Belle II experiment [10].

One of the most recent charmonium-related studies from Belle is a search for the decays $B^+ \to h_c K^+$ and $B^0 \to h_c K^0_S$ [11]. The decays $B^+ \to \chi_{c0} K^+$, $B^+ \to \chi_{c2} K^+$ and $B^+ \to h_c K^+$ are suppressed by factorization. The decays $B^+ \to \chi_{cJ} K^+$ have been observed; the current world-average branching fractions are $\mathcal{B}(B^+ \to \chi_{c0} K^+) = (1.49^{+0.15}_{-0.14}) \times 10^{-4}$ and $\mathcal{B}(B^+ \to \chi_{c2} K^+) = (1.1 \pm 0.4) \times 10^{-5}$ [7]. While $\mathcal{B}(B^+ \to \chi_{c0} K^+)$ is smaller than the branching fraction of the factorization-allowed process $\mathcal{B}(B^+ \to \chi_{c1} K^+) = (4.84 \pm 0.23) \times 10^{-4}$, it is not strongly suppressed. Under the same assumption, the process $B^+ \to h_c K^+$ was expected to have a similar branching fraction $\mathcal{B}(B^+ \to h_c K^+) \approx \mathcal{B}(B^+ \to \chi_{c0} K^+)$. However, the decays $B^+ \to h_c K^+$ and $B^0 \to h_c K^0_S$ have not been observed before. The reported analysis, which benefits from the large Belle data sample, but also from improved discrimination between background and signal events due to multivariate analysis, clearly demonstrates the discovery potential at Belle. As a result of this study, evidence for the decay $B^+ \to h_c K^+$ was found, with a significance of 4.8σ, while no evidence was found for $B^0 \to h_c K^0_S$. The measured branching fraction for the $B^+ \to h_c K^+$ decays is $(3.7^{+1.0}_{-0.9} \pm 0.8) \times 10^{-5}$ while the upper limit for $B^0 \to h_c K^0_S$ branching fraction is 1.4×10^{-5} at 90% confidence level. In addition, a study of the $p\bar{p}\pi^+\pi^-$ invariant mass distribution in the channel $B^+ \to (p\bar{p}\pi^+\pi^-)K^+$ resulted in the first observation of the decay $\eta_c(2S) \to p\bar{p}\pi^+\pi^-$ with more than 12σ significance.

3 Results on Charmed Baryons

Almost a decade after the end of data taking at Belle, a lot of effort is now invested into studies of charmed baryons. Many results were obtained recently and many analyses are still ongoing. The list of results is quite long and it probably deserves a separate contribution. Here, we will therefore mention just one of the published results [12]—observation of the excited Ω^- baryon—while other recent publications are only quoted in the reference section ([14],. . .,[25]).

In the above mentioned analysis [12], a new hyperon was observed. The observed particle is a candidate for an excited Ω^{*-} baryon. These baryons comprise three strange quarks, and have zero isospin. This means that $\Omega^{*-} \to \Omega^-\pi^0$ decays are highly suppressed, which restricts possible decays of excited states, so that the largest expected decay modes are ΞK. This behaviour is analogous to the $\Omega^0_c \to \Xi^+_c K^-$ decays recently discovered by the LHCb Collaboration [13] and confirmed soon after by Belle [16]. The observed new resonance, which is identified as an excited Ω^- baryon, was therefore found in the decay modes $\Omega^{*-} \to \Xi^0 K^-$ and $\Omega^{*-} \to \Xi^- K^0_S$, as expected. The measured mass of the resonance is [2012.4 ± 0.7 (stat) ± 0.6 (syst)] MeV/c^2 and its width, Γ, is [$6.4^{+2.5}_{-2.0}$(stat) ± 1.6 (syst)] MeV. The mass of the new resonance is 340 MeV/c^2 higher than the ground state, which fills the gap in the Ω^- spectrum between the ground state and previously observed excited states. The Ω^{*-} is seen primarily in the decay of the narrow resonances $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ (1). The corresponding data samples, collected with the accelerator energy tuned for the production of the three mentioned Υ resonances, correspond to integrated luminosities of 5.7 fb^{-1}, 24.9 fb^{-1}, and 2.9 fb^{-1}, respectively.

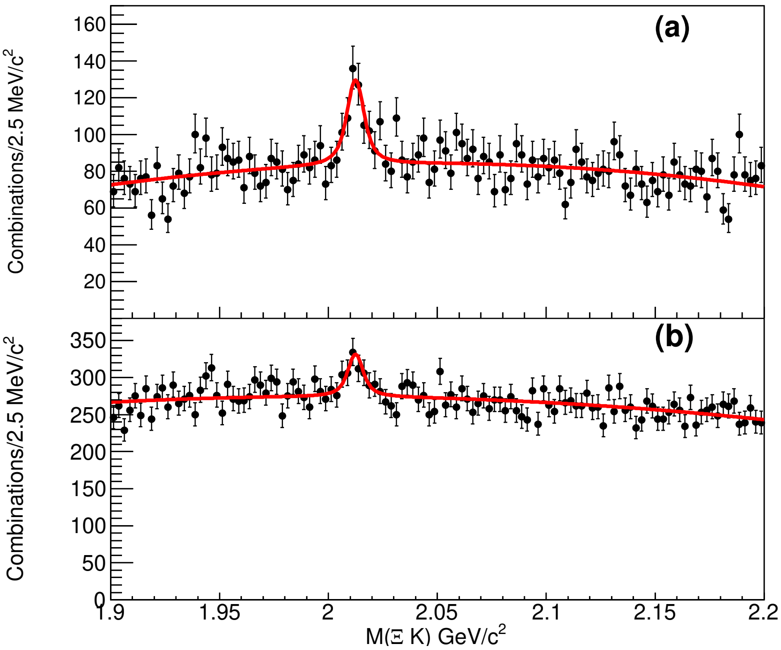

Fig. 1. The (a) $\Xi^0 K^-$ and (b) $\Xi^- K^0_S$ invariant mass distributions in data taken at the energies of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ resonances. The curves show the result of a simultaneous fit to the two distributions with a common mass and width.

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, 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 [10]. Actually, this future has already started, since the completed Belle II detector began its operation at the SuperKEKB collider in March 2019.

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